Foundations

OF NUCLEAR PHYSICS

Facsimiles of THIRTEEN FUNDAMENTAL STUDIES AS THEY WERE ORIGINALLY REPORTED IN THE SCIENTIFIC JOURNALS

With A BIBLIOGRAPHY *compiled by* Robert T. Beyer

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CONTENTS

BIBLIOGRAPHY

FOREWORD

THE COLLECTION of papers in this volume has been prepared with the purpose of bringing within the covers of a single volume the original accounts of fundamental studies in nuclear physics as they were reported by the investigators themselves.

The discovery of the atomic bomb has led to the publication of many texts in which the present knowledge of the nucleus is set forth in detail. The aim of this volume is somewhat different—namely, to give the reader an historical view of nuclear physics, and to bring him into closer contact with the ideas of the leaders of this research.

A few words should be said about the method of selection. These papers represent the original reports of what the editor considers the most momentous hypotheses, discoveries, and inventions in nuclear physics. As criteria of their importance, careful notice has been taken of the frequency with which these papers have been cited by subsequent investigators and of the amount of new research which has been stimulated by them.

The selection of theoretical papers has been particularly difficult because advances in that branch have been made, for the most part, in small steps and by a great number of workers.

The editor realizes that there will be some disagreement on the present selection, particularly concerning papers which have been omitted. He believes this to be a natural consequence of the rapidity with which nuclear physics has developed, and a condition of editorship in general. He points to the limited size of this volume as his defense.

A bibliography of journal articles has been appended which is reasonably complete up to the spring of 1947. It should be pointed out that necessities of type-setting required the use of italics rather than bold-face for the volume numbers of the various journals. Also, the language of the original article is the same as that used in the name of the journal unless otherwise indicated.

ROBERT T. BEYER

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July 1947

PAPERS

MARCH 15, 1933 PHYSICAL REVIEW VOLUME 43

The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*

(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor

ON August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron. Later study of the photograph by a whole group of men of the Norman Bridge Laboratory only tended to strengthen this view. The reason that this interpretation seemed so inevitable is that the track appearing on the upper half of the figure cannot possibly have a mass as large as that of a proton for as soon as the mass is fixed the energy is at once fixed by the curvature. The energy of a proton of that curvature comes out 300,000 volts, but a proton of that energy according to well established and universally accepted determinations[1] has a total range of about 5 mm in air while that portion of the range actually visible in this case exceeds 5 cm without a noticeable change in curvature. The only escape from this conclusion would be to assume that at exactly the same instant (and the sharpness of the tracks determines that instant to within about a fiftieth of a second) two independent electrons happened to produce two tracks so placed as to give the impression of a single particle shooting through the lead plate. This assumption was dismissed on a probability basis, since a sharp track of this order of curvature under the experimental conditions prevailing occurred in the chamber only once in some 500 exposures, and since there was practically no chance at all that two such tracks should line up in this way. We also discarded as completely untenable the assumption of an electron of 20 million volts entering the lead on one side and coming out with an energy of 60 million volts on the other side. A fourth possibility is that a photon, entering the lead from above, knocked out of the nucleus of a lead atom two particles, one of which shot upward and the other downward. But in this case the upward moving one would be a positive of small mass so that either of the two possibilities leads to the existence of the positive electron.

In the course of the next few weeks other photographs were obtained which could be interpreted logically only on the positive-electron basis, and a brief report was then published[2] with due reserve in interpretation in view of the importance and striking nature of the announcement.

MAGNITUDE OF CHARGE AND MASS

It is possible with the present experimental data only to assign rather wide limits to the

[1] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, p. 294. Assuming $R \propto v^3$ and using data there given the range of a 300,000 volt proton in air S.T.P. is about 5 mm.

[2] C. D. Anderson, Science **76**, 238 (1932).

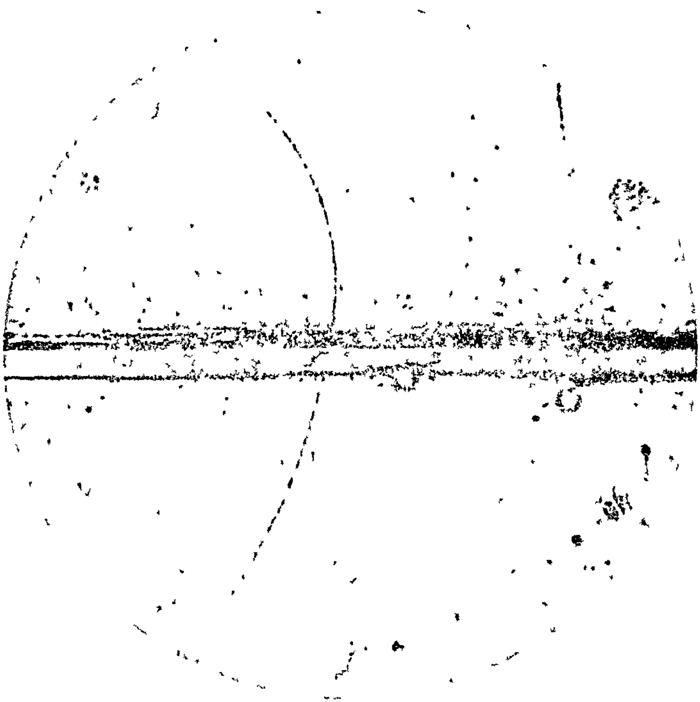


FIG. 1. A 63 million volt positron ($H\rho=2.1\times10^5$ gauss cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho=7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

magnitude of the charge and mass of the particle. The specific ionization was not in these cases measured, but it appears very probable, from a knowledge of the experimental conditions and by comparison with many other photographs of high- and low-speed electrons taken under the same conditions, that the charge cannot differ in magnitude from that of an electron by an amount as great as a factor of two. Furthermore, if the photograph is taken to represent a positive particle penetrating the 6 mm lead plate, then the energy lost, calculated for unit charge, is approximately 38 million electron-volts, this value being practically independent of the proper mass of the particle as long as it is not too many times larger than that of a free negative electron. This value of 63 million volts per cm energy-loss for the positive particle it was considered legitimate to compare with the measured mean of approximately 35 million volts[3] for negative electrons of 200–300 million volts energy since the rate of energy-loss for particles of small mass is expected to change only very slowly over an energy range extending from several million to several hundred million volts. Allowance being made for experimental uncertainties, an upper limit to the rate of loss of energy for the positive particle can then be set at less than four times that for an electron, thus fixing, by the usual relation between rate of ionization and

[3] C. D. Anderson, Phys. Rev. 43, 381A (1933).

charge, an upper limit to the charge less than twice that of the negative electron. It is concluded, therefore, that the magnitude of the charge of the positive electron which we shall henceforth contract to positron is very probably equal to that of a free negative electron which from symmetry considerations would naturally then be called a negatron.

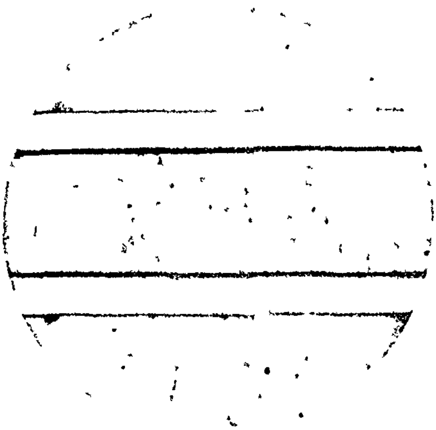


FIG 2 A positron of 20 million volts energy ($H\rho=7.1 \times 10^4$ gauss cm) and a negatron of 30 million volts energy ($H\rho=10.2\times 10^4$ gauss cm) projected from a plate of lead The range of the positive particle precludes the possibility of ascribing it to a proton of the observed curvature

It is pointed out that the effective depth of the chamber in the line of sight which is the same as the direction of the magnetic lines of force was 1 cm and its effective diameter at right angles to that line 14 cm, thus insuring that the particle crossed the chamber practically normal to the lines of force. The change in direction due to scattering in the lead,[3] in this case about 8° measured in the plane of the chamber, is a probable value for a particle of this energy though less than the most probable value.

The magnitude of the proper mass cannot as yet be given further than to fix an upper limit to it about twenty times that of the electron mass If Fig. 1 represents a particle of unit charge passing through the lead plate then the curvatures, on the basis of the information at hand on ionization, give too low a value for the energy-loss unless the mass is taken less than twenty times that of the negative electron mass. Further determinations of $H\rho$ for relatively low energy particles before and after they cross a known amount of matter, together with a study of ballistic effects such as close encounters with electrons, involving large energy transfers, will enable closer limits to be assigned to the mass.

To date, out of a group of 1300 photographs of cosmic-ray tracks 15 of these show positive particles penetrating the lead, none of which can be ascribed to particles with a mass as large as that of a proton, thus establishing the existence of positive particles of unit charge and of mass small compared to that of a proton In many other cases due either to the short section of track available for measurement or to the high energy of the particle it is not possible to differentiate with certainty between protons and positrons A comparison of the six or seven hundred positive-ray tracks which we have taken is, however, still consistent with the view that the positive particle which is knocked out of the nucleus by the incoming primary cosmic ray is in many cases a proton.

FIG 3 A group of six particles projected from a region in the wall of the chamber. The track at the left of the central group of four tracks is a negatron of about 18 million volts energy ($H\rho=6.2\times 10^4$ gauss-cm) and that at the right a positron of about 20 million volts energy ($H\rho=7.0\times 10^4$ gauss-cm) Identification of the two tracks in the center is not possible A negatron of about 15 million volts is shown at the left. This group represents early tracks which were broadened by the diffusion of the ions. The uniformity of this broadening for all the tracks shows that the particles entered the chamber at the same time.

From the fact that positrons occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from an atomic nucleus If we retain the view that a nucleus consists of protons and neutrons (and α-particles) and that a neutron represents a close combination of a proton and electron, then from the electromagnetic theory as to the origin of mass the simplest assumption would seem to be that an encounter between the incoming primary ray and a proton may take place in such a way as to expand the diameter of the proton to the same value as that possessed by the negatron. This process would release an energy of a billion electron-volts appearing as a secondary photon. As a second possibility the primary ray may disintegrate a neutron (or more than one) in the nucleus by the ejection either of a negatron or a positron with the result that a positive or a negative proton, as the case may be, remains in the nucleus in place of the neutron, the event occurring in this instance without the emission of a photon This alternative, however, postulates the existence in the nucleus of a proton of negative charge, no evidence for which exists The greater symmetry, however, between the positive and negative charges revealed by the discovery of the positron should prove a stimulus to search for evidence of the existence of negative protons. If the neutron should prove to be a fundamental particle of a new kind rather than a proton and negatron in close combination, the above hypotheses will have to be abandoned for the proton will then in all probability be represented as a complex particle consisting of a neutron and positron.

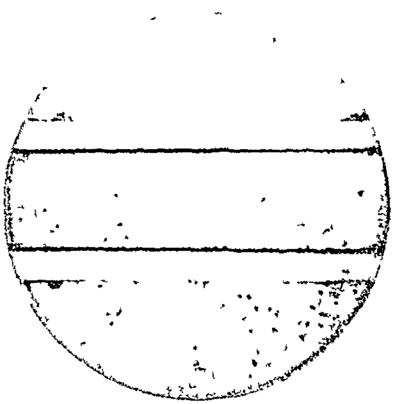


FIG 4 A positron of about 200 million volts energy ($H\rho=6.6\times10^5$ gauss cm) penetrates the 11 mm lead plate and emerges with about 125 million volts energy ($H\rho=4.2\times10^5$ gauss cm) The assumption that the tracks represent a proton traversing the lead plate is inconsistent with the observed curvatures The energies would then be, respectively, about 20 million and 8 million volts above and below the lead, energies too low to permit the proton to have a range sufficient to penetrate a plate of lead of 11 mm thickness

While this paper was in preparation press reports have announced that P. M S. Blackett and G. Occhialini in an extensive study of cosmic-ray tracks have also obtained evidence for the existence of light positive particles confirming our earlier report.

I wish to express my great indebtedness to Professor R. A. Millikan for suggesting this research and for many helpful discussions during its progress The able assistance of Mr. Seth H. Neddermeyer is also appreciated.

The Existence of a Neutron.

By J. Chadwick, F.R.S.

(Received May 10, 1932.)

§ 1. It was shown by Bothe and Becker* that some light elements when bombarded by α-particles of polonium emit radiations which appear to be of the γ-ray type. The element beryllium gave a particularly marked effect of this kind, and later observations by Bothe, by Mme. Curie-Joliot† and by Webster‡ showed that the radiation excited in beryllium possessed a penetrating power distinctly greater than that of any γ-radiation yet found from the radioactive elements. In Webster's experiments the intensity of the radiation was measured both by means of the Geiger-Müller tube counter and in a high pressure ionisation chamber. He found that the beryllium radiation had an absorption coefficient in lead of about $0 \cdot 22$ cm.$^{-1}$ as measured under his experimental conditions. Making the necessary corrections for these conditions, and using the results of Gray and Tarrant to estimate the relative contributions of scattering, photoelectric absorption, and nuclear absorption in the absorption of such penetrating radiation, Webster concluded that the radiation had a quantum energy of about 7×10^6 electron volts. Similarly he found that the radiation from boron bombarded by α-particles of polonium consisted in part of a radiation rather more penetrating than that from beryllium, and he estimated the quantum energy of this component as about 10×10^6 electron volts. These conclusions agree quite well with the supposition that the radiations arise by the capture of the α-particle into the beryllium (or boron) nucleus and the emission of the surplus energy as a quantum of radiation.

The radiations showed, however, certain peculiarities, and at my request the beryllium radiation was passed into an expansion chamber and several photographs were taken. No unexpected phenomena were observed though, as will be seen later, similar experiments have now revealed some rather striking events. The failure of these early experiments was partly due to the weakness of the available source of polonium, and partly to the experimental arrangement, which, as it now appears, was not very suitable.

* 'Z. Physik,' vol. 66, p. 289 (1930).

† I. Curie, 'C. R. Acad. Sci. Paris,' vol. 193, p. 1412 (1931).

‡ 'Proc. Roy. Soc.,' A. vol. 136, p. 428 (1932).

Quite recently, Mme. Curie-Joliot and M. Joliot* made the very striking observation that these radiations from beryllium and from boron were able to eject protons with considerable velocities from matter containing hydrogen. In their experiments the radiation from beryllium was passed through a thin window into an ionisation vessel containing air at room pressure. When paraffin wax, or other matter containing hydrogen, was placed in front of the window, the ionisation in the vessel was increased, in some cases as much as doubled. The effect appeared to be due to the ejection of protons, and from further experiment they showed that the protons had ranges in air up to about 26 cm., corresponding to a velocity of nearly 3×10^9 cm. per second. They suggested that energy was transferred from the beryllium radiation to the proton by a process similar to the Compton effect with electrons, and they estimated that the beryllium radiation had a quantum energy of about 50×10^6 electron volts. The range of the protons ejected by the boron radiation was estimated to be about 8 cm. in air, giving on a Compton process an energy of about 35×10^6 electron volts for the effective quantum.†

There are two grave difficulties in such an explanation of this phenomenon. Firstly, it is now well established that the frequency of scattering of high energy quanta by electrons is given with fair accuracy by the Klein-Nishina formula, and this formula should also apply to the scattering of quanta by a proton. The observed frequency of the proton scattering is, however, many thousand times greater than that predicted by this formula. Secondly, it is difficult to account for the production of a quantum of 50×10^6 electron volts from the interaction of a beryllium nucleus and an α-particle of kinetic energy of 5×10^6 electron volts. The process which will give the greatest amount of energy available for radiation is the capture of the α-particle by the beryllium nucleus, Be^9, and its incorporation in the nuclear structure to form a carbon nucleus C^{13}. The mass defect of the C^{13} nucleus is known both from data supplied by measurements of the artificial disintegration of boron B^{10} and from observations of the band spectrum of carbon; it is about 10×10^6 electron volts. The mass defect of Be^9 is not known, but the assumption that it is zero will give a maximum value for the possible change of energy in the reaction $Be^9 + \alpha \rightarrow C^{13} +$ quantum. On this assumption it follows that the energy of the quantum emitted in such a reaction cannot be greater than about 14×10^6 electron volts. It must, of course, be admitted that this argument

* Curie and Joliot, 'C. R. Acad. Sci. Paris,' vol. 194, p. 273 (1932).

† Many of the arguments of the subsequent discussion apply equally to both radiations, and the term "beryllium radiation" may often be taken to include the boron radiation.

from mass defects is based on the hypothesis that the nuclei are made as far as possible of α-particles; that the Be^9 nucleus consists of 2 α-particles + 1 proton + 1 electron and the C^{13} nucleus of 3 α-particles + 1 proton + 1 electron. So far as the lighter nuclei are concerned, this assumption is supported by the evidence from experiments on artificial disintegration, but there is no general proof.

Accordingly, I made further experiments to examine the properties of the radiation excited in beryllium. It was found that the radiation ejects particles not only from hydrogen but from all other light elements which were examined. The experimental results were very difficult to explain on the hypothesis that the beryllium radiation was a quantum radiation, but followed immediately if it were supposed that the radiation consisted of particles of mass nearly equal to that of a proton and with no net charge, or neutrons. A short statement of some of these observations was published in 'Nature.'* This paper contains a fuller description of the experiments, which suggest the existence of neutrons and from which some of the properties of these particles can be inferred. In the succeeding paper Dr. Feather will give an account of some observations by means of the expansion chamber of the collisions between the beryllium radiation and nitrogen nuclei, and this is followed by an account by Mr. Dee of experiments to observe the collisions with electrons.

§ 2. *Observations of Recoil Atoms.*—The properties of the beryllium radiation were first examined by means of the valve counter used in the work† on the artificial disintegration by α-particles and described fully there. Briefly, it consists of a small ionisation chamber connected to a valve amplifier. The sudden production of ions in the chamber by the entry of an ionising particle is detected by means of an oscillograph connected in the output circuit of the amplifier. The deflections of the oscillograph were recorded photographically on a film of bromide paper.

The source of polonium was prepared from a solution of radium (D+E+F)‡ by deposition on a disc of silver. The disc had a diameter of 1 cm. and was placed close to a disc of pure beryllium of 2 cm. diameter, and both were enclosed in a small vessel which could be evacuated, fig. 1. The first ionisation chamber used had an opening of 13 mm. covered with aluminium foil of 4·5 cm. air equivalent, and a depth of 15 mm. This chamber had a very low natural effect, giving on the average only about 7 deflections per hour.

* 'Nature,' vol. 129, p. 312 (1932).

† Chadwick, Constable and Pollard, 'Proc. Roy. Soc.,' A, vol. 130, p. 463 (1931).

‡ The radium D was obtained from old radon tubes generously presented by Dr. C. F. and Dr. F. West, of the Kelly Hospital, Baltimore.

When the source vessel was placed in front of the ionisation chamber, the number of deflections immediately increased. For a distance of 3 cm. between the beryllium and the counter the number of deflections was nearly 4 per minute. Since the number of deflections remained sensibly the same when thick metal sheets, even as much as 2 cm. of lead, were interposed between the source vessel and the counter, it was clear that these deflections were due to a penetrating radiation emitted from the beryllium. It will be shown later that the deflections were due to atoms of nitrogen set in motion by the impact of the beryllium radiation.

When a sheet of paraffin wax about 2 mm. thick was interposed in the path of the radiation just in front of the counter, the number of deflections recorded by the oscillograph increased markedly. This increase was due to particles

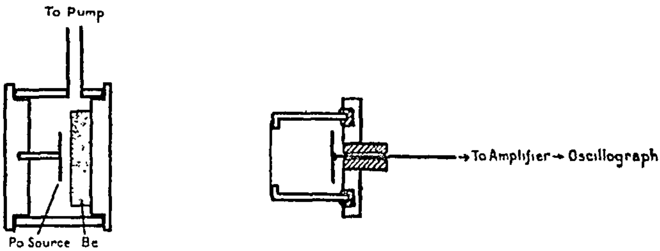


Fig. 1.

ejected from the paraffin wax so as to pass into the counter. By placing absorbing screens of aluminium between the wax and the counter the absorption curve shown in fig. 2, curve A, was obtained. From this curve it appears that the particles have a maximum range of just over 40 cm. of air, assuming that an Al foil of 1·64 mg. per square centimetre is equivalent to 1 cm. of air. By comparing the sizes of the deflections (proportional to the number of ions produced in the chamber) due to these particles with those due to protons of about the same range it was obvious that the particles were protons. From the range-velocity curve for protons we deduce therefore that the maximum velocity imparted to a proton by the beryllium radiation is about $3 \cdot 3 \times 10^9$ cm. per second, corresponding to an energy of about $5 \cdot 7 \times 10^6$ electron volts.

The effect of exposing other elements to the beryllium radiation was then investigated. An ionisation chamber was used with an opening covered with a gold foil of 0·5 mm. air equivalent. The element to be examined was fixed on a clean brass plate and placed very close to the counter opening. In this way lithium, beryllium, boron, carbon and nitrogen, as paracyanogen, were

tested. In each case the number of deflections observed in the counter increased when the element was bombarded by the beryllium radiation. The ranges of the particles ejected from these elements were quite short, of the order of some millimetres in air. The deflections produced by them were of different sizes, but many of them were large compared with the deflection produced even by a slow proton. The particles therefore have a large ionising power and are probably in each case recoil atoms of the elements. Gases were investigated by filling the ionisation chamber with the required gas by circulation for several minutes. Hydrogen, helium, nitrogen, oxygen, and argon were examined in this way. Again, in each case deflections were observed which were attributed to the production of recoil atoms in the different gases. For a given position of the beryllium source relative to the counter, the number of recoil atoms was roughly the same for each gas. This point will be referred to later. It appears then that the beryllium radiation can impart energy to the atoms of matter through which it passes and that the chance of an energy transfer does not vary widely from one element to another.

It has been shown that protons are ejected from paraffin wax with energies up to a maximum of about $5 \cdot 7 \times 10^6$ electron volts. If the ejection be ascribed to a Compton recoil from a quantum of radiation, then the energy of the quantum must be about 55×10^6 electron volts, for the maximum energy which can be given to a mass m by a quantum $h\nu$ is $\frac{2}{2 + mc^2/h\nu} \cdot h\nu$. The energies of the recoil atoms produced by this radiation by the same process in other elements can be readily calculated. For example, the nitrogen recoil atoms should have energies up to a maximum of 450,000 electron volts. Taking the energy necessary to form a pair of ions in air as 35 electron volts, the recoil atoms of nitrogen should produce not more than about 13,000 pairs of ions. Many of the deflections observed with nitrogen, however, corresponded to far more ions than this ; some of the recoil atoms produced from 30,000 to 40,000 ion pairs. In the case of the other elements a similar discrepancy was noted between the observed energies and ranges of the recoil atoms and the values calculated on the assumption that the atoms were set in motion by recoil from a quantum of 55×10^6 electron volts. The energies of the recoil atoms were estimated from the number of ions produced in the counter, as given by the size of the oscillograph deflections. A sufficiently good measurement of the ranges could be made either by varying the distance between the element and the counter or by interposing thin screens of gold between the element and the counter.

The nitrogen recoil atoms were also examined, in collaboration with Dr. N. Feather, by means of the expansion chamber. The source vessel was placed immediately above an expansion chamber of the Shimizu type, so that a large proportion of the beryllium radiation traversed the chamber. A large number of recoil tracks was observed in the course of a few hours. Their range, estimated by eye, was sometimes as much as 5 or 6 mm. in the chamber, or, correcting for the expansion, about 3 mm. in standard air. These visual estimates were confirmed by a preliminary series of experiments by Dr. Feather with a large automatic expansion chamber, in which photographs of the recoil tracks in nitrogen were obtained. Now the ranges of recoil atoms of nitrogen of different velocities have been measured by Blackett and Lees. Using their results we find that the nitrogen recoil atoms produced by the beryllium radiation may have a velocity of at least 4×10^8 cm. per second, corresponding to an energy of about $1 \cdot 2 \times 10^6$ electron volts. In order that the nitrogen nucleus should acquire such an energy in a collision with a quantum of radiation, it is necessary to assume that the energy of the quantum should be about 90×10^6 electron volts, if energy and momentum are conserved in the collision. It has been shown that a quantum of 55×10^6 electron volts is sufficient to explain the hydrogen collisions. In general, the experimental results show that if the recoil atoms are to be explained by collision with a quantum, we must assume a larger and larger energy for the quantum as the mass of the struck atom increases.

§ 3. *The Neutron Hypothesis.*—It is evident that we must either relinquish the application of the conservation of energy and momentum in these collisions or adopt another hypothesis about the nature of the radiation. If we suppose that the radiation is not a quantum radiation, but consists of particles of mass very nearly equal to that of the proton, all the difficulties connected with the collisions disappear, both with regard to their frequency and to the energy transfer to different masses. In order to explain the great penetrating power of the radiation we must further assume that the particle has no net charge. We may suppose it to consist of a proton and an electron in close combination, the "neutron" discussed by Rutherford* in his Bakerian Lecture of 1920.

When such neutrons pass through matter they suffer occasionally close

* Rutherford, 'Proc. Roy. Soc.,' A, vol. 97, p. 374 (1920). Experiments to detect the formation of neutrons in a hydrogen discharge tube were made by J. L. Glasson, 'Phil. Mag.,' vol. 42, p. 596 (1921), and by J. K. Roberts, 'Proc. Roy. Soc.,' A, vol. 102, p. 72 (1922). Since 1920 many experiments in search of these neutrons have been made in this laboratory.

collisions with the atomic nuclei and so give rise to the recoil atoms which are observed. Since the mass of the neutron is equal to that of the proton, the recoil atoms produced when the neutrons pass through matter containing hydrogen will have all velocities up to a maximum which is the same as the maximum velocity of the neutrons. The experiments showed that the maximum velocity of the protons ejected from paraffin wax was about $3 \cdot 3 \times 10^9$ cm. per second. This is therefore the maximum velocity of the neutrons emitted from beryllium bombarded by α-particles of polonium. From this we can now calculate the maximum energy which can be given by a colliding neutron to other atoms, and we find that the results are in fair agreement with the energies observed in the experiments. For example, a nitrogen atom will acquire in a head-on collision with the neutron of mass 1 and velocity $3 \cdot 3 \times 10^9$ cm. per second a velocity of $4 \cdot 4 \times 10^8$ cm. per second, corresponding to an energy of $1 \cdot 4 \times 10^6$ electron volts, a range of about $3 \cdot 3$ mm. in air, and a production of ions of about 40,000 pairs. Similarly, an argon atom may acquire an energy of $0 \cdot 54 \times 10^6$ electron volts, and produce about 15,000 ion pairs. Both these values are in good accord with experiment.*

It is possible to prove that the mass of the neutron is roughly equal to that of the proton, by combining the evidence from the hydrogen collisions with that from the nitrogen collisions. In the succeeding paper, Feather records experiments in which about 100 tracks of nitrogen recoil atoms have been photographed in the expansion chamber. The measurement of the tracks shows that the maximum range of the recoil atoms is $3 \cdot 5$ mm. in air at 15° C. and 760 mm. pressure, corresponding to a velocity of $4 \cdot 7 \times 10^8$ cm. per second according to Blackett and Lees. If M, V be the mass and velocity of the neutron then the maximum velocity given to a hydrogen atom is

$$u_p = \frac{2M}{M+1} \cdot V,$$

and the maximum velocity given to a nitrogen atom is

$$u_n = \frac{2M}{M+14} \cdot V,$$

whence

$$\frac{M+14}{M+1} = \frac{u_p}{u_n} = \frac{3 \cdot 3 \times 10^9}{4 \cdot 7 \times 10^8},$$

* It was noted that a few of the nitrogen recoil atoms produced about 50 to 60,000 ion pairs. These probably correspond to the cases of disintegration found by Feather and described in his paper.

and

$$M = 1 \cdot 15.$$

The total error in the estimation of the velocity of the nitrogen recoil atom may easily be about 10 per cent., and it is legitimate to conclude that the mass of the neutron is very nearly the same as the mass of the proton.

We have now to consider the production of the neutrons from beryllium by the bombardment of the α-particles. We must suppose that an α-particle is captured by a Be^9 nucleus with the formation of a carbon C^{12} nucleus and the emission of a neutron. The process is analogous to the well-known artificial disintegrations, but a neutron is emitted instead of a proton. The energy relations of this process cannot be exactly deduced, for the masses of the Be^9 nucleus and the neutron are not known accurately. It is, however, easy to show that such a process fits the experimental facts. We have

$$\begin{aligned} &Be^9 + He^4 + \text{kinetic energy of } \alpha \\ &\qquad = C^{12} + n^1 + \text{kinetic energy of } C^{12} + \text{kinetic energy of } n^1. \end{aligned}$$

If we assume that the beryllium nucleus consists of two α-particles and a neutron, then its mass cannot be greater than the sum of the masses of these particles, for the binding energy corresponds to a defect of mass. The energy equation becomes

$$\begin{aligned} (8 \cdot 00212 + n^1) + 4 \cdot 00106 + \text{K.E. of } \alpha > 12 \cdot 0003 + n^1 \\ + \text{K.E. of } C^{12} + \text{K.E. of } n^1 \end{aligned}$$

or

$$\text{K.E. of } n^1 < \text{K.E. of } \alpha + 0 \cdot 003 - \text{K.E. of } C^{12}.$$

Since the kinetic energy of the α-particle of polonium is $5 \cdot 25 \times 10^6$ electron volts, it follows that the energy of emission of the neutron cannot be greater than about 8×10^6 electron volts. The velocity of the neutron must therefore be less than $3 \cdot 9 \times 10^9$ cm. per second. We have seen that the actual maximum velocity of the neutron is about $3 \cdot 3 \times 10^9$ cm. per second, so that the proposed disintegration process is compatible with observation.

A further test of the neutron hypothesis was obtained by examining the radiation emitted from beryllium in the opposite direction to the bombarding α-particles. The source vessel, fig. 1, was reversed so that a sheet of paraffin wax in front of the counter was exposed to the "backward" radiation from the beryllium. The maximum range of the protons ejected from the wax was determined as before, by counting the numbers of protons observed through different thicknesses of aluminium interposed between the wax and the counter.

The absorption curve obtained is shown in curve B, fig. 2. The maximum range of the protons was about 22 cm. in air, corresponding to a velocity of about $2 \cdot 74 \times 10^9$ cm. per second. Since the polonium source was only about 2 mm. away from the beryllium, this velocity should be compared with that of the neutrons emitted not at 180° but at an angle not much greater than 90°

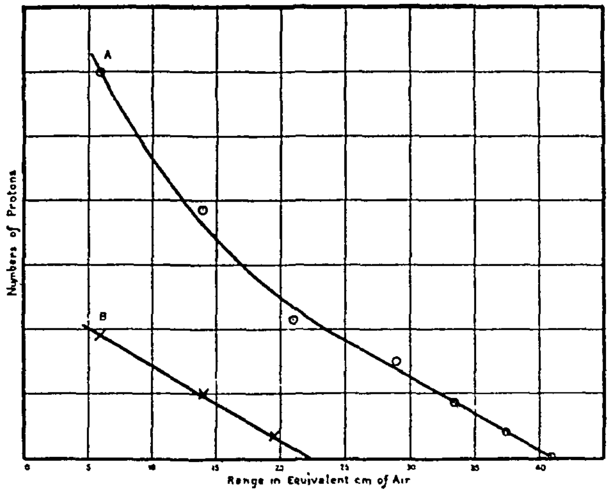


FIG. 2.

to the direction of the incident α-particles. A simple calculation shows that the velocity of the neutron emitted at 90° when an α-particle of full range is captured by a beryllium nucleus should be $2 \cdot 77 \times 10^9$ cm. per second, taking the velocity of the neutron emitted at 0° in the same process as $3 \cdot 3 \times 10^9$ cm. per second. The velocity found in the above experiment should be less than this, for the angle of emission is slightly greater than 90°. The agreement with calculation is as good as can be expected from such measurements.

§ 4. *The Nature of the Neutron.*—It has been shown that the origin of the radiation from beryllium bombarded by α-particles and the behaviour of the radiation, so far as its interaction with atomic nuclei is concerned, receive a simple explanation on the assumption that the radiation consists of particles of mass nearly equal to that of the proton which have no charge. The simplest hypothesis one can make about the nature of the particle is to suppose that it consists of a proton and an electron in close combination, giving a net charge 0 and a mass which should be slightly less than the mass of the hydrogen atom. This hypothesis is supported by an examination of the evidence which can be obtained about the mass of the neutron.

As we have seen, a rough estimate of the mass of the neutron was obtained from measurements of its collisions with hydrogen and nitrogen atoms, but such measurements cannot be made with sufficient accuracy for the present purpose. We must turn to a consideration of the energy relations in a process in which a neutron is liberated from an atomic nucleus; if the masses of the atomic nuclei concerned in the process are accurately known, a good estimate of the mass of the neutron can be deduced. The mass of the beryllium nucleus has, however, not yet been measured, and, as was shown in § 3, only general conclusions can be drawn from this reaction. Fortunately, there remains the case of boron. It was stated in § 1 that boron bombarded by α-particles of polonium also emits a radiation which ejects protons from materials containing hydrogen. Further examination showed that this radiation behaves in all respects like that from beryllium, and it must therefore be assumed to consist of neutrons. It is probable that the neutrons are emitted from the isotope B^{11}, for we know that the isotope B^{10} disintegrates with the emission of a proton.* The process of disintegration will then be

$$B^{11} + He^{4} \rightarrow N^{14} + n^{1}.$$

The masses of B^{11} and N^{14} are known from Aston's measurements, and the further data required for the deduction of the mass of the neutron can be obtained by experiment.

In the source vessel of fig. 1 the beryllium was replaced by a target of powdered boron, deposited on a graphite plate. The range of the protons ejected by the boron radiation was measured in the same way as with the beryllium radiation. The effects observed were much smaller than with beryllium, and it was difficult to measure the range of the protons accurately. The maximum range was about 16 cm. in air, corresponding to a velocity of $2 \cdot 5 \times 10^{9}$ cm. per second. This then is the maximum velocity of the neutron liberated from boron by an α-particle of polonium of velocity $1 \cdot 59 \times 10^{9}$ cm. per second. Assuming that momentum is conserved in the collision, the velocity of the recoiling N^{14} nucleus can be calculated, and we then know the kinetic energies of all the particles concerned in the disintegration process. The energy equation of the process is

$$\begin{aligned} &\text{Mass of } B^{11} + \text{mass of } He^{4} + \text{K.E. of } He^{4} \\ &\qquad = \text{mass of } N^{14} + \text{mass of } n^{1} + \text{K.E. of } N^{14} + \text{K.E. of } n^{1}. \end{aligned}$$

* Chadwick, Constable and Pollard, *loc. cit.*

The masses are $B^{11} = 11{\cdot}00825 \pm 0{\cdot}0016$; $He^4 = 4{\cdot}00106 \pm 0{\cdot}0006$; $N^{14} = 14{\cdot}0042 \pm 0{\cdot}0028$. The kinetic energies in mass units are α-particle $= 0{\cdot}00565$; neutron $= 0{\cdot}0035$; and nitrogen nucleus $= 0{\cdot}00061$. We find therefore that the mass of the neutron is 1·0067. The errors quoted for the mass measurements are those given by Aston. They are the maximum errors which can be allowed in his measurements, and the probable error may be taken as about one-quarter of these.* Allowing for the errors in the mass measurements it appears that the mass of the neutron cannot be less than 1·003, and that it probably lies between 1·005 and 1·008.

Such a value for the mass of the neutron is to be expected if the neutron consists of a proton and an electron, and it lends strong support to this view. Since the sum of the masses of the proton and electron is 1·0078, the binding energy, or mass defect, of the neutron is about 1 to 2 million electron volts. This is quite a reasonable value. We may suppose that the proton and electron form a small dipole, or we may take the more attractive picture of a proton embedded in an electron. On either view, we may expect the "radius" of the neutron to be a few times 10^{-13} cm.

§ 5. *The Passage of the Neutron through Matter.*—The electrical field of a neutron of this kind will clearly be extremely small except at very small distances of the order of 10^{-12} cm. In its passage through matter the neutron will not be deflected unless it suffers an intimate collision with a nucleus. The potential of a neutron in the field of a nucleus may be represented roughly by fig. 3. The radius of the collision area for sensible deflection of the neutron

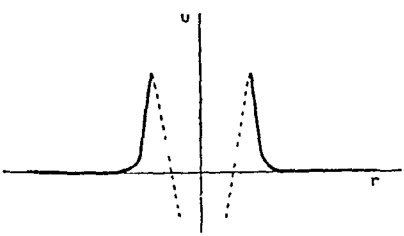


FIG. 3.

will be little greater than the radius of the nucleus. Further, the neutron should be able to penetrate the nucleus easily, and it may be that the scattering of the neutrons will be largely due to the internal field of the nucleus, or, in other words, that the scattered neutrons are mainly those which have penetrated

* The mass of B^{11} relative to B^{10} has been checked by optical methods by Jenkins and McKellar ('Phys. Rev.,' vol. 39, p. 549 (1932)). Their value agrees with Aston's to 1 part in 10^4. This suggests that great confidence may be put in Aston's measurements.

the potential barrier. On these views we should expect the collisions of a neutron with a nucleus to occur very seldom, and that the scattering will be roughly equal in all directions, at least as compared with the Coulomb scattering of a charged particle.

These conclusions were confirmed in the following way. The source vessel, with Be target, was placed rather more than 1 inch from the face of a closed counter filled with air, fig. 1. The number of deflections, or the number of nitrogen recoil atoms produced in the chamber, was observed for a certain time. The number observed was 190 per hour, after allowing for the natural effect. A block of lead 1 inch thick was then introduced between the source vessel and the counter. The number of deflections fell to 166 per hour. Since the number of recoil atoms produced must be proportional to the number of neutrons passing through the counter, these observations show that 13 per cent. of the neutrons had been absorbed or scattered in passing through 1 inch of lead.

Suppose that a neutron which passes within a distance p from the centre of the lead nucleus is scattered and removed from the beam. Then the fraction removed from the beam in passing through a thickness t of lead will be $\pi p^2 nt$, where n is the number of lead atoms per unit volume. Hence $\pi p^2 nt = 0 \cdot 13$, and $p = 7 \times 10^{-13}$ cm. This value for the collision radius with lead seems perhaps rather small, but it is not unreasonable. We may compare it with the radii of the radioactive nuclei calculated from the disintegration constants by Gamow and Houtermans,* viz., about 7×10^{-13} cm.

Similar experiments were made in which the neutron radiation was passed through blocks of brass and carbon. The values of p deduced in the same way were 6×10^{-13} cm. and $3 \cdot 5 \times 10^{-13}$ cm. respectively.

The target areas for collision for some light elements were compared by another method. The second ionisation chamber was used, which could be filled with different gases by circulation. The position of the source vessel was kept fixed relative to the counter, and the number of deflections was observed when the counter was filled in turn with hydrogen, nitrogen, oxygen, and argon. Since the number of neutrons passing through the counter was the same in each case, the number of deflections should be proportional to the target area for collision, neglecting the effect of the material of the counter, and allowing for the fact that argon is monatomic. It was found that nitrogen, oxygen, and argon gave about the same number of deflections; the target areas of nitrogen and oxygen are thus roughly equal, and the target area of argon is

* 'Z. Physik,' vol. 52, p. 453 (1928).

nearly twice that of these. With hydrogen the measurements were very difficult, for many of the deflections were very small owing to the low ionising power of the proton and the low density of the gas. It seems probable from the results that the target area of hydrogen is about two-thirds that of nitrogen or oxygen, but it may be rather greater than this.

There is as yet little information about the angular distribution of the scattered neutrons. In some experiments kindly made for me by Dr. Gray and Mr. Lea, the scattering by lead was compared in the backward and forward directions, using the ionisation in a high pressure chamber to measure the neutrons. They found that the amount of scattering was about that to be expected from the measurements quoted above, and that the intensity per unit solid angle was about the same between 30° to 90° in the forward direction as between 90° to 150° in the backward direction. The scattering by lead is therefore not markedly anisotropic.

Two types of collision may prove to be of peculiar interest, the collision of a neutron with a proton and the collision with an electron. A detailed study of these collisions with an elementary particle is of special interest, for it should provide information about the structure and field of the neutron, whereas the other collisions will depend mainly on the structure of the atomic nuclei. Some preliminary experiments by Mr. Lea, using the pressure chamber to measure the scattering of neutrons by paraffin wax and by liquid hydrogen, suggest that the collision with a proton is more frequent than with other light atoms. This is not in accord with the experiments described above, but the results are at present indecisive. These collisions can be more directly investigated by means of the expansion chamber or by counting methods, and it is hoped to do so shortly.

The collision of a neutron with an electron has been examined in two ways, by the expansion chamber and by the counter. An account of the expansion chamber experiments is given by Mr. Dee in the third paper of this series. Mr. Dee has looked for the general ionisation produced by a large number of neutrons in passing through the expansion chamber, and also for the short electron tracks which should be the result of a very close collision between a neutron and an electron. His results show that collisions with electrons are extremely rare compared even with those with nitrogen nuclei, and he estimates that a neutron can produce on the average not more than 1 ion pair in passing through 3 metres of air.

In the counter experiments a beam of neutrons was passed through a block of brass, 1 inch thick, and the maximum range of the protons ejected from

paraffin wax by the emergent beam was measured. From this range the maximum velocity of the neutrons after travelling through the brass is obtained and it can be compared with the maximum velocity in the incident beam. No change in the velocity of the neutrons due to their passage through the brass could be detected. The accuracy of the experiment is not high, for the estimation of the end of the range of the protons was rather difficult. The results show that the loss of energy of a neutron in passing through 1 inch of brass is not more than about $0 \cdot 4 \times 10^6$ electron volts. A path of 1 inch in brass corresponds as regards electron collisions to a path of nearly 2×10^4 cm. of air, so that this result would suggest that a neutron loses less than 20 volts per centimetre path in air in electron collisions. This experiment thus lends general support to those with the expansion chamber, though it is of far inferior accuracy. We conclude that the transfer of energy from the neutron to electrons is of very rare occurrence. This is not unexpected. Bohr* has shown on quite general ideas that collisions of a neutron with an electron should be very few compared with nuclear collisions. Massey,† on plausible assumptions about the field of the neutron, has made a detailed calculation of the loss of energy to electrons, and finds also that it should be small, not more than 1 ion pair per metre in air.

General Remarks.

It is of interest to examine whether other elements, besides beryllium and boron, emit neutrons when bombarded by α-particles. So far as experiments have been made, no case comparable with these two has been found. Some evidence was obtained of the emission of neutrons from fluorine and magnesium, but the effects were very small, rather less than 1 per cent. of the effect obtained from beryllium under the same conditions. There is also the possibility that some elements may emit neutrons spontaneously, *e.g.*, potassium, which is known to emit a nuclear β-radiation accompanied by a more penetrating radiation. Again no evidence was found of the presence of neutrons, and it seems fairly certain that the penetrating type is, as has been assumed, a γ-radiation.

Although there is certain evidence for the emission of neutrons only in two cases of nuclear transformations, we must nevertheless suppose that the neutron is a common constituent of atomic nuclei. We may then proceed to build up nuclei out of α-particles, neutrons and protons, and we are able to

* Bohr, Copenhagen discussions, unpublished.

† Massey, 'Nature,' vol. 129, p. 469, corrected p. 691 (1932).

avoid the presence of uncombined electrons in a nucleus. This has certain advantages for, as is well known, the electrons in a nucleus have lost some of the properties which they have outside, *e.g.*, their spin and magnetic moment. If the α-particle, the neutron, and the proton are the only units of nuclear structure, we can proceed to calculate the mass defect or binding energy of a nucleus as the difference between the mass of the nucleus and the sum of the masses of the constituent particles. It is, however, by no means certain that the α-particle and the neutron are the only complex particles in the nuclear structure, and therefore the mass defects calculated in this way may not be the true binding energies of the nuclei. In this connection it may be noted that the examples of disintegration discussed by Dr. Feather in the next paper are not all of one type, and he suggests that in some cases a particle of mass 2 and charge 1, the hydrogen isotope recently reported by Urey, Brickwedde and Murphy, may be emitted. It is indeed possible that this particle also occurs as a unit of nuclear structure.

It has so far been assumed that the neutron is a complex particle consisting of a proton and an electron. This is the simplest assumption and it is supported by the evidence that the mass of the neutron is about 1·006, just a little less than the sum of the masses of a proton and an electron. Such a neutron would appear to be the first step in the combination of the elementary particles towards the formation of a nucleus. It is obvious that this neutron may help us to visualise the building up of more complex structures, but the discussion of these matters will not be pursued further for such speculations, though not idle, are not at the moment very fruitful. It is, of course, possible to suppose that the neutron may be an elementary particle. This view has little to recommend it at present, except the possibility of explaining the statistics of such nuclei as N^{14}.

There remains to discuss the transformations which take place when an α-particle is captured by a beryllium nucleus, Be^9. The evidence given here indicates that the main type of transformation is the formation of a C^{12} nucleus and the emission of a neutron. The experiments of Curie-Joliot and Joliot,* of Auger,† and of Dee show quite definitely that there is some radiation emitted by beryllium which is able to eject fast electrons in passing through matter. I have made experiments using the Geiger point counter to investigate this radiation and the results suggest that the electrons are produced by a

* 'C. R. Acad. Sci. Paris,' vol. 194, p. 708 and p. 876 (1932).

† 'C. R. Acad. Sci. Paris,' vol. 194, p. 877 (1932).

γ-radiation. There are two distinct processes which may give rise to such a radiation. In the first place, we may suppose that the transformation of Be^9 to C^{12} takes place sometimes with the formation of an excited C^{12} nucleus which goes to the ground state with the emission of γ-radiation. This is similar to the transformations which are supposed to occur in some cases of disintegration with proton emission, *e.g.*, B^{10}, F^{19}, Al^{27}; the majority of transformations occur with the formation of an excited nucleus, only in about one-quarter is the final state of the residual nucleus reached in one step. We should then have two groups of neutrons of different energies and a γ-radiation of quantum energy equal to the difference in energy of the neutron groups. The quantum energy of this radiation must be less than the maximum energy of the neutrons emitted, about $5 \cdot 7 \times 10^6$ electron volts. In the second place, we may suppose that occasionally the beryllium nucleus changes to a C^{13} nucleus and that all the surplus energy is emitted as radiation. In this case the quantum energy of the radiation may be about 10×10^6 electron volts.

It is of interest to note that Webster has observed a soft radiation from beryllium bombarded by polonium α-particles, of energy about 5×10^5 electron volts. This radiation may well be ascribed to the first of the two processes just discussed, and its intensity is of the right order. On the other hand, some of the electrons observed by Curie-Joliot and Joliot had energies of the order of 2 to 10×10^6 volts, and Auger recorded one example of an electron of energy about $6 \cdot 5 \times 10^6$ volts. These electrons may be due to a hard γ-radiation produced by the second type of transformation.*

It may be remarked that no electrons of greater energy than the above appear to be present. This is confirmed by an experiment† made in this laboratory by Dr. Occhialini. Two tube counters were placed in a horizontal plane and the number of coincidences recorded by them was observed by means of the method devised by Rossi. The beryllium source was then brought up in the plane of the counters so that the radiation passed through both counters in turn. No increase in the number of coincidences could be detected. It follows that there are few, if any, β-rays produced with energies sufficient to pass through the walls of both counters, a total of 4 mm. brass; that is, with energies greater than about 6×10^6 volts. This experiment further shows that the neutrons very rarely produce coincidences in tube counters under the usual conditions of experiment.

* Although the presence of fast electrons can be easily explained in this way, the possibility that some may be due to secondary effects of the neutrons must not be lost sight of.

† *Cf.* also Rasetti, 'Naturwiss.,' vol. 20, p. 252 (1932).

In conclusion, I may restate briefly the case for supposing that the radiation the effects of which have been examined in this paper consists of neutral particles rather than of radiation quanta. Firstly, there is no evidence from electron collisions of the presence of a radiation of such a quantum energy as is necessary to account for the nuclear collisions. Secondly, the quantum hypothesis can be sustained only by relinquishing the conservation of energy and momentum. On the other hand, the neutron hypothesis gives an immediate and simple explanation of the experimental facts; it is consistent in itself and it throws new light on the problem of nuclear structure.

Summary.

The properties of the penetrating radiation emitted from beryllium (and boron) when bombarded by the α-particles of polonium have been examined. It is concluded that the radiation consists, not of quanta as hitherto supposed, but of neutrons, particles of mass 1, and charge 0. Evidence is given to show that the mass of the neutron is probably between 1·005 and 1·008. This suggests that the neutron consists of a proton and an electron in close combination, the binding energy being about 1 to 2 $\times$ 10^6 electron volts. From experiments on the passage of the neutrons through matter the frequency of their collisions with atomic nuclei and with electrons is discussed.

I wish to express my thanks to Mr. H. Nutt for his help in carrying out the experiments.

equality of the total separations and the relatively inverted positions of the levels due to the two isotopes 199 and 201. The structure now proposed shows that the anomaly noted by Schüler and Keyston regarding the magnitudes of the isotope displacements and the fine intervals does not exist in the $6\,^1P_1$ level.

In conclusion, we should like to record our deepest thanks to Professor Venkatesachar for his guidance and encouragement throughout this work. One of us is indebted to the University of Mysore for the award of a scholarship.

Experiments with High Velocity Positive Ions. II.—*The Disintegration of Elements by High Velocity Protons.*

By J. D. Cockcroft, Ph.D., Fellow of St. John's College, Cambridge, and E. T. S. Walton, Ph.D.

(Communicated by Lord Rutherford, O.M., F.R.S.—Received June 15, 1932.)

[Plate 12.]

1. *Introduction.*

In a previous paper* we have described a method of producing high velocity positive ions having energies up to 700,000 electron volts. We first used this method to determine the range of high-speed protons in air and hydrogen and the results obtained will be described in a subsequent paper. In the present communication we describe experiments which show that protons having energies above 150,000 volts are capable of disintegrating a considerable number of elements.

Experiments in artificial disintegration have in the past been carried out with streams of α-particles as the bombarding particles ; the resulting transmutations have in general been accompanied by the emission of a proton and in some cases γ-radiation.† The present experiments show that under the bombardment of protons, α-particles are emitted from many elements ; the disintegration process is thus in a sense the reverse process to the α-particle transformation.

* 'Proc. Roy. Soc.,' A, vol. 136, p. 619 (1932) denoted as (I) hereafter.

† Rutherford, Chadwick and Ellis, "Radioactive Substances."

2. *The Experimental Method.*

Positive ions of hydrogen obtained from a hydrogen canal ray tube are accelerated by voltages up to 600 kilovolts in the experimental tube described in (I) and emerge through a 3-inch diameter brass tube into a chamber well shielded by lead and screened from electrostatic fields. To this brass tube is attached by a flat joint and plasticene seal the apparatus shown in fig. 1. A target, A, of the metal to be investigated is placed at an angle of 45 degrees to the direction of the proton stream. Opposite the centre of the target is a side tube across which is sealed at B either a zinc sulphide screen or a mica window.

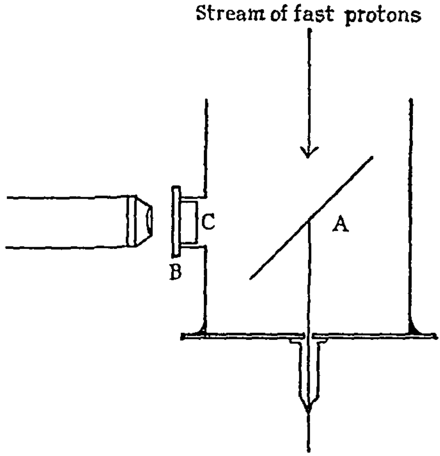


Fig. 1.

In our first experiments we used a round target of lithium 5 cm. in diameter and sealed the side tube with a zinc sulphide screen, the sensitive surface being towards the target. The distance from the centre of the target to the screen was 5 cm. A sheet of mica, C, of stopping power 1·4 cm. was placed between the screen and target and was more than adequate to prevent any scattered protons reaching the screen, since our range determinations* and the experiments of Blackett† have shown that the maximum range of protons accelerated by 600 kilovolts is of the order of 10 mm. in air. The screen is observed with a microscope having a numerical aperture of 0·6, the area of screen covered being 12 sq. mm. This arrangement with the fluorescent surface inside the vacuum is generally used in the preliminary investigations

* In course of publication.

† 'Proc. Roy. Soc.' A, vol. 134, p. 658 (1931).

of elements and when it is necessary to detect the presence of particles of short range.

The current to the target is measured by a galvanometer and controlled by varying the speed of the motor used for driving the alternator exciting the discharge tube (see Paper I). Currents of up to 5 microamperes can be obtained. Since metals bombarded by high-speed positive ions emit large numbers of secondary electrons for each incident ion, it is necessary to prevent the emission of these electrons if an accurate determination of the number of incident ions is required. This has been effected by applying a magnetic field of the order of 700 gauss to the target. Since it is well known that the majority of the secondary electrons have energies below 20 volts, such a field should be adequate to prevent secondary electron emission being a serious source of error.

An accurate determination of the exact composition of the beam of ions has not yet been made, but deflection experiments with a magnetic field in a subsidiary apparatus have shown that approximately half the current is carried by protons and half by H_2^+ ions. The number of neutral atoms appears to be small.

The accelerating voltage used in the experiments is controlled by varying the field of the alternator exciting the main high tension transformer. The secondary voltage of this transformer is measured by the method described in an earlier paper,* which rectifies the current passing through a condenser. A microammeter on the control table allows a continuous reading of this voltage to be obtained. The value of the steady potential produced by the rectifier system varies between 3 and 3·5 times the maximum of the transformer voltage according to the brightness of the rectifier filaments. The actual value of the voltage is determined by using a sphere gap consisting of two 75-cm. diameter aluminium spheres, one of which is earthed. In each experiment the multiplication factor of the rectifier system is determined for several voltages and intermediate points obtained by interpolation. The accuracy of the determination of the voltage by the sphere gaps has been checked by measuring the deflection of the protons in a magnetic field. It has been found that corrections of the order of 15 per cent. may be required as a result of the proximity of neighbouring objects or unfavourable arrangements of the connecting leads. The voltages given in this paper have all been corrected by reference to the magnetic deflection experiments.

* 'Proc. Roy. Soc.' A, vol. 129, p. 477 (1930).

3. *The Disintegration of Lithium.*

When the current passing to the target was of the order of 1 microampere and the accelerating potential was increased to 125 kilovolts, a number of bright scintillations were observed on the screen, the numbers being proportional to the current collected and of the order of 5 per minute per microampere at 125 kilovolts.

No scintillations were observed when the proton current was cut off by shutting off the discharge tube excitation or by interposing a brass flap between the beam and the target. Since the scintillations were very similar in appearance and brightness to α-particle scintillations, the apparatus was now changed to allow a determination of their range to be made. For this purpose a mica window having a stopping power of 2 cm. was sealed to the side tube in place of the fluorescent screen, which was now placed outside the window. It was then possible to insert mica screens of known stopping power between the window and the screen. In this way it became apparent that the scintillations were produced by particles having a well-defined range of about 8 cm. Variations of voltage between 250 and 500 kilovolts did not appear to alter the range appreciably.

In order to check this conclusion, the particles were now passed into a Shimizu expansion chamber, through a mica window in the side of the chamber having a stopping power of 3·6 cm. When the accelerating voltage was applied to the tube a number of discrete tracks were at once observed in the chamber whose lengths agreed closely with the first range determinations. From the appearance of the tracks and the brightness of the scintillations it seemed now fairly clear that we were observing α-particles ejected from the lithium nuclei under the proton bombardment, and that the lithium isotope of mass 7 was breaking up into two α-particles.

In order to obtain a further proof of the nature of the particles the experiments were repeated with an ionisation chamber, amplifier and oscillograph of the type described by Wynn Williams and Ward.* The mica window on the side tube was reduced to a thickness corresponding to a stopping power of 1·2 mm. with an area of about 1 sq. cm., the mica being supported on a grid structure. The lithium target was at the same time reduced in size to a circle of 1 cm. diameter in order to reduce the angular spread of the particles entering the counter. The ionisation chamber was of the parallel plane type having a total depth of 3 mm. and was sealed by an aluminium window having a stopping

* 'Proc. Roy. Soc.,' A, vol. 132, p. 391 (1931).

power of 5 mm. The degree of resolution of the amplifier and oscillograph was such that it was possible to record accurately up to 2000 particles per minute. With the full potential applied to the apparatus but with no proton current, the number of spurious deflections in the oscillograph was of the order of 2 per minute, whilst with an accelerating potential of 500 kilovolts and a current of 0·3 microamperes the number of particles entering the ionisation chamber per minute was of the order of 700.

In figs. 8, 9, 10 and 11, Plate 12, are shown the oscillograph records obtained as additional mica absorbers are inserted. It will be seen that the size of the deflections increases as additional mica is inserted, whilst the numbers fall off rapidly when the total absorber thickness is increased beyond 7 cm. In fig. 2 is plotted the number of particles entering the chamber per minute per microampere for increasing absorber thickness and for accelerating potentials of 270 kilovolts and 450 kilovolts. The stopping power of the mica screens of windows has been checked and the final range determination made by a comparison with the α-particles from thorium C. We find that the range is 8·4 cm. Preliminary observations showed that between the lowest and highest voltages used, the range remained approximately constant. It is, however, of great interest to test whether the whole of the energy of the proton is communicated to the α-particles, and it is intended at a later date to examine this point more carefully. The general shape of the range curve, together with the evidence from the size of the oscillograph deflections, suggests that the great majority of the particles have initially a uniform velocity, but further investigation will be required with lower total absorption to exclude the possibility of the existence of particles of short range.

As is well known, the size of the oscillograph kicks are a measure of the ionisation produced by the particles. At the beginning of the range the size of the kicks observed was very uniform, whilst the average size varied with the range of the particle corresponding to the ionisation given by the Bragg curve. Fig. 3 shows the variation of the ionisation of the most numerous particles with range.

The sizes of the deflections were now compared with the deflections produced in the same ionisation chamber by α-particles from a polonium source, these deflections being recorded in fig. 12, Plate 12, for comparison. It has been shown in this way that the maximum deflection for the two types of particle is the same. This result, together with the uniformity of the ionisation produced by the particles. is sufficient to exclude the possibility of some of the particles being protons, since the maximum ionisation produced by

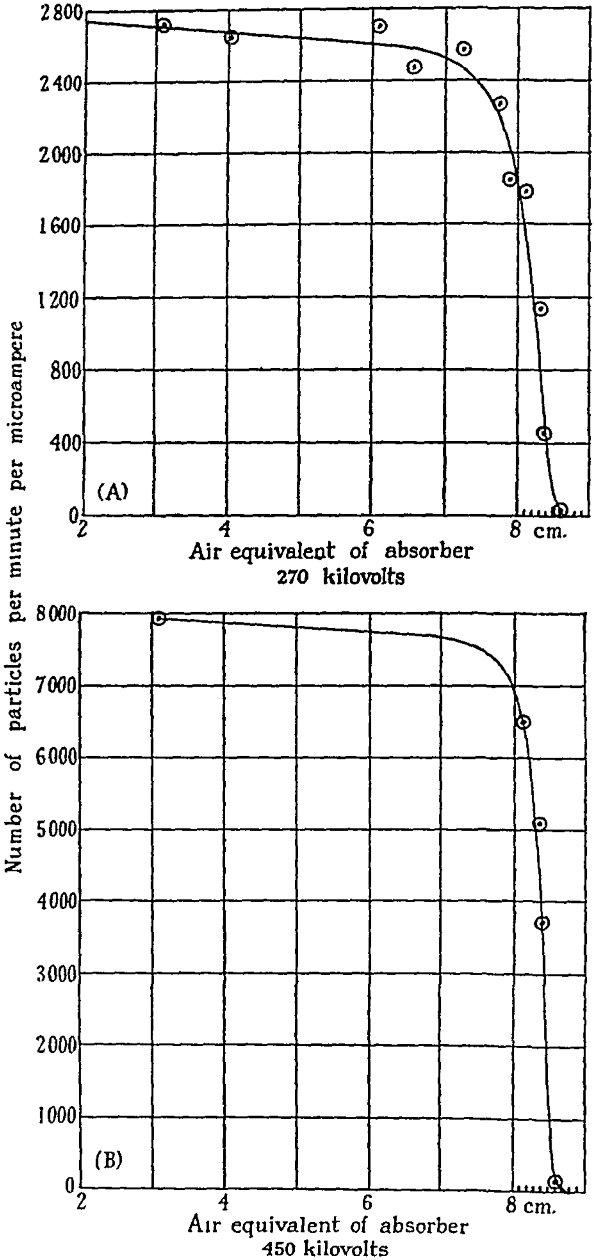

2800
2400
2000
1600
1200
800
400
0
(A)
2
4
6
8 cm.
Air equivalent of absorber
270 kilovolts
Number of particles per minute per microampere
8000
7000
6000
5000
4000
3000
2000
1000
0
(B)
2
4
6
8 cm.
Air equivalent of absorber
450 kilovolts

Fig. 2.

proton is less than 40 per cent. of the maximum ionisation produced by an α-particle.

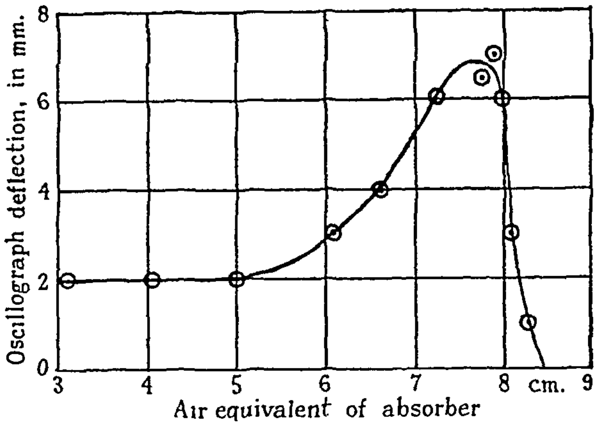


FIG. 3.

The variation of the numbers of particles with accelerating voltage was determined from the oscillograph records between 200 kilovolts and 500 kilovolts, the change in numbers being clear from the records, figs. 13, 14, 15, Plate 12. For voltages between 70 kilovolts and 250 kilovolts, the numbers of particles entering the ionisation chamber were counted by a single stage thyratron counter of the type described by Wynn Williams and Ward.* The results are plotted in fig. 4. The numbers increase roughly exponentially with the voltage at the lower voltages and linearly with voltage above 300 kilovolts.†

It is of great interest to estimate the number of particles produced by the bombardment of a thick layer of lithium by a fixed number of protons. In making this estimate we have assumed that the particles are emitted uniformly in all directions and that the molecular ions produce no effect. With these assumptions the number of disintegrations for a voltage of 250 kilovolts is 1 per 10^9 protons, and for a voltage of 500 kilovolts is 10 per 10^9 protons.

In considering the variation in numbers of particles with voltage it has, of course, to be borne in mind that with a thick target the effects are due to

* 'Proc. Roy. Soc.,' A, vol. 131, p. 191 (1931).

† All the measurements in a single run, in which more than 2000 particles were counted are included in the figure. The spread of the points in the centre part of the curve is probably due to variations in the vacuum and therefore in the voltage applied during the experiment. In other runs no evidence was obtained for such a variation.

protons of all energies from the maximum to zero energy. It will be very important to determine the probability of disintegration for protons of one definite energy, and for this purpose it will be necessary to use thin targets. Preliminary experiments using evaporated films of lithium show that the probability or " excitation " function does not increase so rapidly with voltage as for the thick target, but owing to the small numbers of particles obtainable these experiments have not yet been completed.

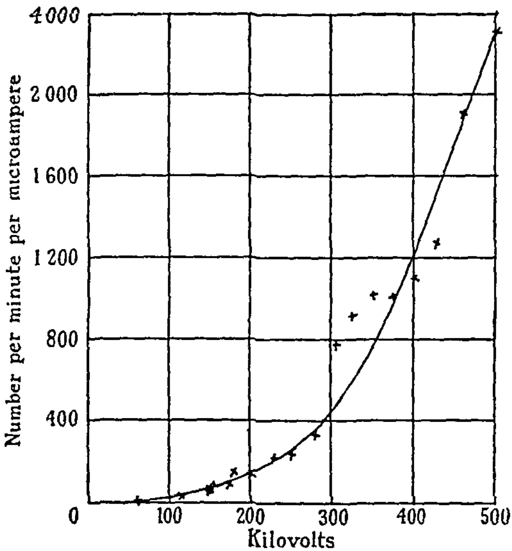


Fig. 4.

4. *The Interpretation of Results.*

We have already stated that the obvious interpretation of our results is to assume that the lithium isotope of mass 7 captures a proton and that the resulting nucleus of mass 8 breaks up into two α-particles. If momentum is conserved in the process, then each of the α-particles must take up equal amounts of energy, and from the observed range of the α-particles we conclude that an energy of 17·2 million volts would be liberated in this disintegration process. The mass of the Li_7 nucleus from Costa's determination is 7·0104 with a probable error of 0·003. The decrease of mass in the disintegration process is therefore $7 \cdot 0104 + 1 \cdot 0072 - 8 \cdot 0022 = 0 \cdot 0154 \pm 0 \cdot 003$. This is equivalent to an energy liberation of $(14 \cdot 3 \pm 2 \cdot 7) \times 10^6$ volts. We conclude, therefore, that the observed energies of the α-particles are consistent with our

hypothesis. An additional test can, however, be applied. If momentum is conserved in the disintegration, the two α-particles must be ejected in practically opposite directions and, therefore, if we arrange two zinc sulphide screens opposite to a small target of lithium as shown in the arrangement of fig. 5, we should observe a large proportion of coincidences in the time of appearance of the scintillations on the two screens. The lithium used in the experiments was evaporated on to a thin film of mica having an area of 1 sq. mm. and a stopping power of 1·1 cm., so that α-particles ejected from the lithium would pass easily through the mica and reach the screen on the opposite side of the lithium layer.

The two screens were observed through microscopes each covering an area of 7 sq. mm. and a tape recording machine was used to record the scintillations,

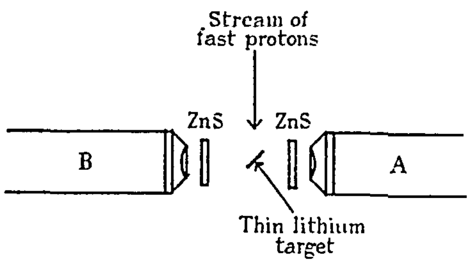


Fig. 5.

a buzzer being installed in the observation chamber to prevent the noise of the recording keys being audible to the observers. Five hundred and sixty-five scintillations were observed in microscope A and 288 scintillations in microscope B, the former being nearer the target. Analysis of the records showed that the results are consistent with the assumption that about 25 per cent. of the scintillations recorded in B have a corresponding scintillation in A. If we calculate the chance of a scintillation being recorded by B within x seconds of the record of a scintillation in A, assuming a perfectly random distribution of scintillations, and compare this with the observed record, the curve shown in fig. 6 is obtained. It will be seen that as the interval x is made less, the ratio of the observed to the random coincidences increases. We also plot for comparison the theoretical curve (shown by broken line) which would be obtained if there were 25 per cent. of coincidences. It will be seen that the two curves are in good accord. The number of coincidences observed is about that to be expected on our theory of the disintegration process, when we take into account the geometry of the experimental arrangement and the efficiency of the zinc

sulphide screens. It is clear that there is strong evidence supporting the hypothesis that the α-particles are emitted in pairs. A more complete investigation will be made later, using larger areas for the counting device, when it is to be expected that the fraction of coincidences should increase.

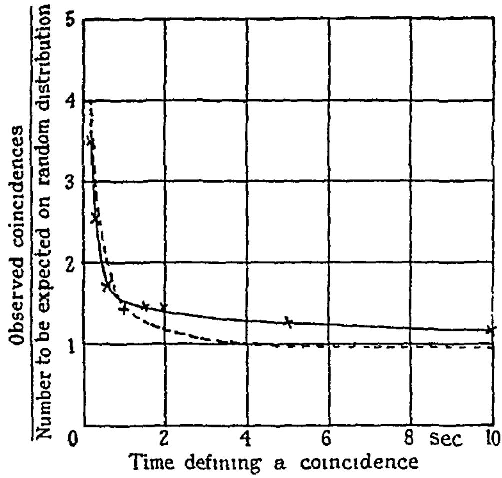


FIG. 6.

5. *Comparison with the Gamow Theory.*

In a paper which was largely responsible for stimulating the present investigation, Gamow† has calculated the probability $W_1{}^*$ of a particle of charge Ze, mass m and energy E, entering a nucleus of charge $Z'e$. Gamow's formula is

$$W_1{}^* = e^{\frac{-4\pi\sqrt{(2m)}}{h} \cdot \frac{ZZ'e^2}{\sqrt{(E)}} \cdot J_k},$$

where J_k is a function varying slowly with E and Z. Using this formula, we have calculated $W_1{}^*$, the probability of a proton entering a lithium nucleus, for 600, 300 and 100 kilovolts, and find the values 0·187. $2 \cdot 75 \times 10^{-2}$ and $1 \cdot 78 \times 10^{-4}$. Using these figures, our observed variation of proton range with velocity for a thick target, and assuming a target area of 10^{-25} cm.^{2}, the number of protons N required to produce one disintegration may be calculated. For 600 kilovolts we find N to be of the order of 10^6, and for 300 kilovolts of the order of 2×10^7.

The order of magnitude of the numbers observed is thus smaller than the

† 'Z. Physik,' vol. 52, p. 510 (1928).

number predicted by the Gamow theory, but a closer comparison must be deferred until the results for a thin target are available.

6. *The Disintegration of other Elements.*

Preliminary investigations have been made to determine whether any evidence of disintegration under proton bombardment could be obtained for the following elements : Be, B, C, O, F, Na, Al, K, Ca, Fe, Co, Ni, Cu, Ag, Pb, U. Using the fluorescent screen as a detector we have observed some bright scintillations from all these elements, the numbers varying markedly from element to element, the relative orders of magnitude being indicated by fig. 7 for 300 kilovolts. The results of the scintillation method have been confirmed by the electrical counter for Ca, K, Ni, Fe and Co, and the size of the oscillograph kicks suggests that the majority of the particles ejected are α-particles.

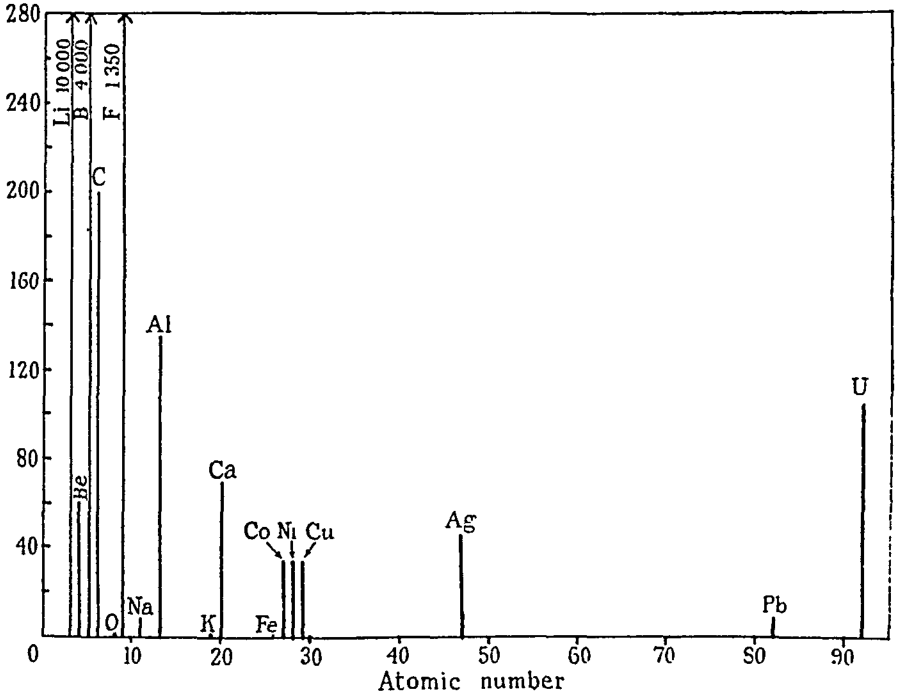


Fig. 7.

The numbers of particles counted have up to the present not been sufficient to enable these figures to be taken as anything other than an order of magnitude. In particular, the possibility must be borne in mind that some of the particles observed may be due to impurities. It may, however, be of some interest to

describe briefly the general character of the effects observed in some of the more interesting cases.

Beryllium.—Two types of scintillation were observed with beryllium, a few bright scintillations having the appearance of α-particle scintillations together with a much greater number of faint scintillations appearing at about 500 kilovolts, the numbers increasing rapidly with voltage. We were not able to observe the faint scintillations outside the vacuum chamber, so that they are presumably due to particles of short range.

Boron.—Next to lithium, boron gave the greatest number of scintillations, most of the particles having a range of about 3·5 cm. Scintillations were first observed at voltages of the order of 115 kilovolts, the numbers increasing by more than 100 between this voltage and 375 kilovolts. The interesting problem as to whether the boron splits up into three α-particles or into Be_8 plus an α-particle must await an answer until more detailed investigation is made.

Fluorine.—Fluorine was investigated in the form of a layer of powdered calcium fluoride. A few scintillations were first observed at a voltage of 200 kilovolts, the numbers increasing by a factor of about 100 between this and 450 kilovolts. The range of the particles was found to be about 2·8 cm. On the assumption that they are α-particles, the energy would be $4 \cdot 15 \times 10^6$ electron volts. If now we assume that the reaction is

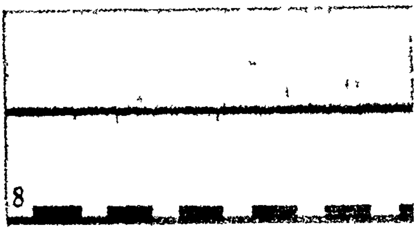
$$F_{19} + H_1 = O_{16} + He_4$$

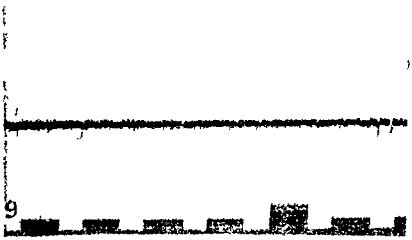
it is of particular interest to compare the observed energy with the energy to be expected from the mass changes, since all the masses involved are known, from the work of Aston, with fairly good precision.

Using Aston's data, the energy liberated should be $5 \cdot 2 \times 10^6$ electron volts. Allowing for the energy taken by the recoil of the oxygen nucleus and the energy of the bombarding proton, the energy of the α-particle should be about 4·3 million volts, giving a range of 2·95 cm. in air, in good accord with the observed ranges.

Sodium.—A small number of bright scintillations were observed beginning at 300 kilovolts, the particles having ranges between 2 and 3·5 cm. In addition to the bright scintillations, a number of faint scintillations were observed similar to those seen in the case of beryllium. The faint scintillations are again presumably due to particles of short range since they could not be observed outside the tube. The probable α-particle transition would be

$$Na_{23} + H_1 = Ne_{20} + He_4.$$





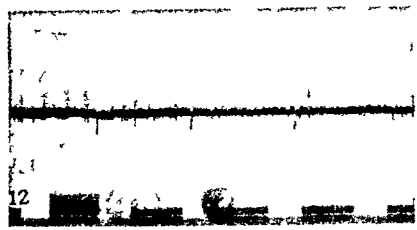


FIG. 8.—270 Kv. 4·0 cm. absorber.

FIG. 9.—270 Kv. 5·0 cm. absorber.

FIG. 10.—270 Kv 6·6 cm. absorber.

FIG. 11.—270 Kv. 7·9 cm. absorber.

FIG. 12.—Polonium α-particles 2 cm. absorber.

FIG. 13.—250 Kv. 3·1 cm. absorber.

FIG. 14.—210 Kv. 3·1 cm. absorber

FIG. 15.—175 Kv. 3·1 cm. absorber.

Potassium.—Potassium is of special interest on account of its radioactivity. The very small effects observed may easily be due to an impurity. The most likely reaction to occur

$$K_{39} + H_1 = A_{36} + He_4,$$

would probably have a negative energy balance.

Iron, Nickel, Cobalt, Copper.—These elements follow each other in the periodic table, so that the small result obtained for iron compared with that for the following three elements is of special interest. The effect for iron is of the same order as that for potassium, and again may be due to impurity. For these elements most of the particles had a range of about 2·5 cm., but a few particles were present having a slightly longer range.

Uranium.—Using potentials of up to 600 kilovolts and strong proton currents, the number of scintillations observed was about four times the natural radioactive effect, and the artificially produced particles appeared to have a longer range than the natural ones. The numbers obtained did not appear to vary markedly with voltage.

We hope in the near future to investigate the above and other elements in much greater detail and in particular to determine whether any of the effects described are due to impurities. There seems to be little doubt, however, that most of the effects are due to transformations giving rise to an α-particle emission. In view of the very small probability of a proton of 500 kilovolts energy penetrating the potential barrier of the heavier nuclei by any process other than a resonance process, it would appear most likely that such processes are responsible for the effects observed with the heavier elements.

We have seen that the three elements, lithium, boron and fluorine give the largest emission of particles, the emission varying similarly with rise of voltage. These elements are all of the $4n + 3$ type, and presumably the nuclei are made up of α-particles with the addition of three protons and two electrons. It is natural to suppose that the addition of a captured proton leads to the formation of a new α-particle inside the nucleus. In the case of lithium, it seems probable that the capture of the proton, the formation of the α-particle and the disintegration of the resulting nucleus into two α-particles must at this stage be regarded as a single process, the excess energy appearing in the form of kinetic energy of the expelled α-particles.* Until further and more accurate data are available it is not desirable to discuss at this stage the possible bearing of

* Such a view does not preclude the possibility that sometimes part of the energy may appear in another form, for example, as γ-radiation.

these new observations on the problems of astrophysics and on the question of the abundance of the elements.

In conclusion, we wish to express our thanks to Lord Rutherford for his constant encouragement and advice. We are indebted to Dr. Wynn Williams for considerable assistance with the electrical recording apparatus, and to members of the research staff of Metropolitan-Vickers Electrical Company for their assistance in supplying much of the apparatus used in this work. One of us (E.T.S.W.) has been in receipt of a senior research award from the Department of Scientific and Industrial Research.

PHYSIQUE NUCLÉAIRE. — *Un nouveau type de radioactivité.* Note de Mme **Irène Curie** et M. **F. Joliot**, présentée par M. Jean Perrin.

Nous avons montré récemment par la méthode de Wilson (1) que certains éléments légers (glucinium, bore, aluminium) émettent des électrons positifs quand on les bombarde avec des rayons α du polonium. Selon notre interprétation l'émission des électrons positifs de Be serait due à la *matérialisation interne* du rayonnement γ tandis que les électrons positifs émis par B et Al seraient des *électrons de transmutation* accompagnant l'émission des neutrons.

En cherchant à préciser le mécanisme de ces émissions nous avons découvert le phénomène suivant :

L'émission des électrons positifs par certains éléments légers irradiés par les rayons α du polonium subsiste pendant des temps plus ou moins longs, pouvant atteindre plus d'une demi-heure dans le cas du bore, après l'enlèvement de la source de rayons α.

Nous plaçons une feuille d'aluminium à 1mm d'une source de polonium. L'aluminium ayant été irradié pendant 10 minutes environ, nous le plaçons au-dessus d'un compteur de Geiger Müller portant un orifice fermé par un écran de 7/100e de millimètre d'aluminium. Nous observons que la feuille émet un rayonnement dont l'intensité décroît exponentiellement en fonction du temps avec une période de 3 minutes 15 secondes. On obtient un résultat analogue avec le bore et le magnésium mais les périodes de décroissance sont *différentes*, 14 minutes pour le bore et 2 minutes 30 secondes pour le magnésium.

L'intensité du rayonnement (immédiatement après l'exposition aux rayons α) augmente avec le temps d'irradiation jusqu'à une valeur limite. On a alors des intensités initiales du même ordre pour B, Mg, Al d'environ 150 impulsions par minute dans le compteur en utilisant une source de polonium de 60 millicuries.

Avec les éléments H, Li, C, Be, N, O, F, Na, Ca, Ni, Ag, aucun effet n'a été observé (2). Pour certain de ces éléments le phénomène ne se produit probablement pas, pour d'autres la période de décroissance est peut-être trop courte.

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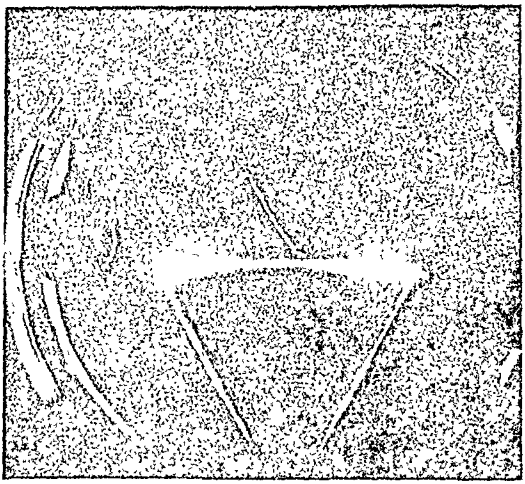
(1) *Comptes rendus*, 196, 1933, p. 1885; *J. de Phys. et Rad.*, 4, 1933, p. 494.

(2) Ce phénomène ne peut donc pas être dû à une contamination par la source de polonium.

Les expériences faites par la méthode de Wilson ou par la méthode de la trochoïde introduite par Thibaud ont montré que le rayonnement émis par le bore et par l'aluminium est constitué par des électrons positifs. Il est probable qu'il en est de même pour le rayonnement du magnésium.

En introduisant des écrans de cuivre entre le compteur et la feuille irradiée on trouve que la majeure partie du rayonnement est absorbée dans



0,88 g/cm² pour Al, 0,26 g/cm² pour B et Mg, ce qui correspond, en admettant les mêmes lois d'absorption que pour les électrons négatifs, à une énergie de $2,2 \times 10^6\,eV$ pour Al et $0,7 \times 10^6\,eV$ pour B et Mg.

Lorsqu'on réduit l'énergie des rayons α irradiant l'aluminium, le nombre des électrons positifs diminue, mais la période de décroissance ne semble pas modifiée. Quand l'énergie des rayons α est réduite de $10^6\,eV$, on n'observe presque plus de ces électrons.

Ces expériences montrent l'existence d'un nouveau type de radioactivité avec émission d'électrons positifs. Nous pensons que le processus d'émission serait le suivant pour l'aluminium :

$$^{27}_{13}\mathrm{Al} + ^{4}_{2}\mathrm{He} = ^{30}_{15}\mathrm{P} + ^{1}_{0}n.$$

L'isotope $^{30}_{15}P$ du phosphore serait radioactif avec une période de $3^m 15^s$ et émettrait des électrons positifs suivant la réaction

$$^{30}_{15}\mathrm{P} = ^{30}_{14}\mathrm{Si} + \overset{+}{\varepsilon}.$$

Une réaction analogue pourrait être envisagée pour le bore et le magnésium, les noyaux instables étant ${}^{13}_{7}N$ et ${}^{27}_{14}Si$. Les isotopes ${}^{13}_{7}N$, ${}^{27}_{14}Si$, ${}^{30}_{15}P$ ne peuvent exister que des temps assez courts, c'est pourquoi on ne les observerait pas dans la nature.

Nous considérons comme peu vraisemblable l'explication suivant laquelle

$$ {}^{27}_{13}Al + {}^{4}_{2}He = {}^{30}_{14}Si + {}^{1}_{1}H, \qquad {}^{30}_{14}Si = {}^{30}_{14}Si + \overset{+}{\varepsilon} + \overset{-}{\varepsilon}, $$

l'isotope ${}^{30}_{14}Si$ étant excité et pouvant se désactiver au cours du temps, l'énergie se matérialiserait en donnant une paire d'électrons. On n'observe pas d'émission d'électrons négatifs et il est théoriquement très improbable que la différence d'énergie entre les électrons soit suffisante pour que les négatifs ne soient pas observés (1). D'autre part ce processus supposerait une durée de l'état excité extraordinairement longue avec un coefficient de matérialisation interne unité.

En définitive il a été possible pour la première fois de créer à l'aide d'une cause extérieure la radioactivité de certains noyaux atomiques pouvant subsister un temps mesurable en l'absence de la cause excitatrice.

Des radioactivités durables, analogues à celles que nous avons observé, peuvent sans doute exister dans le cas de bombardement par d'autres particules. Un même atome radioactif pourrait sans doute être créé par plusieurs réactions nucléaires. Par exemple le noyau ${}^{13}_{7}N$ qui est radioactif selon notre hypothèse, pourrait être obtenu par l'action d'un deuton sur le carbone, après émission d'un neutron.

CHIMIE PHYSIQUE. — *Étude cinétique de la réaction iodure de potassium-eau oxygénée en solution acide.* Note de Mme P. Rumpf, présentée par M. G. Urbain.

L'eau oxygénée et l'iodure de potassium réagissent en solution acide en donnant naissance à de l'iode. La cinétique de cette réaction a été l'objet de nombreux travaux; les auteurs ont généralement dosé l'iode mis en liberté; plus récemment, Abel (2), puis Liebhafsky (3) ont mesuré le dégagement d'oxygène au fur et à mesure de la décomposition de l'eau oxygénée. Cependant la question reste obscure; il a semblé intéressant de l'aborder

(1) Nedelsky et Oppenheimer, *Phys. Rev.*, 44, 1933, p. 948.
(2) *Zeit. phys. Chem.*, 96, 1920, p. 1-180, et 136, 1928, p. 161-182.
(3) *J. amer. chem. Soc.*, 54, 1932, p. 1792-1806 et 3499-3508.

ERRATA.

(Séance du 15 janvier 1934.)

Note de Mme *Irène Curie* et M. *F. Joliot*, Un nouveau type de radioactivité :

La figure représentée page 255 doit être supprimée.

Possible Production of Elements of Atomic Number Higher than 92

By PROF. E. FERMI, Royal University of Rome

UNTIL recently it was generally admitted that an atom resulting from artificial disintegration should normally correspond to a stable isotope. M. and Mme. Joliot first found evidence that it is not necessarily so; in some cases the product atom may be radioactive with a measurable mean life, and go over to a stable form only after emission of a positron.

The number of elements which can be activated either by the impact of an α-particle (Joliot) or a proton (Cockcroft, Gilbert, Walton) or a deuton (Crane, Lauritsen, Henderson, Livingston, Lawrence) is necessarily limited by the fact that only light elements can be disintegrated, owing to the Coulomb repulsion.

This limitation is not effective in the case of neutron bombardment. The high efficiency of these particles in producing disintegrations compensates fairly for the weakness of available neutron sources as compared with α-particle or proton sources. As a matter of fact, it has been shown[1] that a large number of elements (47 out of 68 examined until now) of any atomic weight could be activated, using neutron sources consisting of a small glass tube filled with beryllium powder and radon up to 800 millicuries. This source gives a yield of about one million neutrons per second.

All the elements activated by this method with intensity large enough for a magnetic analysis of the sign of the charge of the emitted particles were found to give out only negative electrons. This is theoretically understandable, as the absorption of the bombarding neutron produces an excess in the number of neutrons present inside the nucleus; a stable state is therefore reached generally through transformation of a neutron into a proton, which is connected to the emission of a β-particle.

In several cases it was possible to carry out a chemical separation of the β-active element, following the usual technique of adding to the irradiated substance small amounts of the neighbouring elements. These elements are then separated by chemical analysis and separately checked for the β-activity with a Geiger-Müller counter. The activity always followed completely a certain element, with which the active element could thus be identified.

In three cases (aluminium, chlorine, cobalt) the active element formed by bombarding the element of atomic number Z has atomic number $Z-2$. In four cases (phosphorus, sulphur, iron, zinc) the atomic number of the active product is $Z-1$. In two cases (bromine, iodine) the active element is an isotope of the bombarded element.

This evidence seems to show that three main processes are possible: (a) capture of a neutron with instantaneous emission of an α-particle; (b) capture of the neutron with emission of a

proton; (c) capture of the neutron with emission of a γ-quantum, to get rid of the surplus energy. From a theoretical point of view, the probability of processes (a) and (b) depends very largely on the energy of the emitted α- or H-particle; the more so the higher the atomic weight of the element. The probability of process (c) can be evaluated only very roughly in the present state of nuclear theory; nevertheless, it would appear to be smaller than the observed value by a factor 100 or 1,000.

It seemed worth while to direct particular attention to the heavy radioactive elements thorium and uranium, as the general instability of nuclei in this range of atomic weight might give rise to successive transformations. For this reason an investigation of these elements was undertaken by the writer in collaboration with F. Rasetti and O. D'Agostino.

Experiment showed that both elements, previously freed of ordinary active impurities, can be strongly activated by neutron bombardment. The initial induced activity corresponded in our experiments to about 1,000 impulses per minute in a Geiger counter made of aluminium foil of 0·2 mm. thickness. The curves of decay of these activities show that the phenomenon is rather complex. A rough survey of thorium activity showed in this element at least two periods.

Better investigated is the case of uranium; the existence of periods of about 10 sec., 40 sec., 13 min., plus at least two more periods from 40 minutes to one day is well established. The large uncertainty in the decay curves due to the statistical fluctuations makes it very difficult to establish whether these periods represent successive or alternative processes of disintegration.

Attempts have been made to identify chemically the β-active element with the period of 13 min. The general scheme of this research consisted in adding to the irradiated substance (uranium nitrate in concentrated solution, purified of its decay products) such an amount of an ordinary β-active element as to give some hundred impulses per minute on the counter. Should it be possible to prove that the induced activity, recognisable by its characteristic period, can be chemically separated from the added activity, it is reasonable to assume that the two activities are not due to isotopes.

The following reaction enables one to separate the 13 min.-product from most of the heaviest elements. The irradiated uranium solution is diluted in 50 per cent nitric acid; a small amount of a manganese salt is added and then the manganese is precipitated as dioxide (MnO_2) from the boiling solution by addition of sodium chlorate. The manganese dioxide precipitate carries a large percentage of the activity.

This reaction proves at once that the 13 min.-activity is not isotopic with uranium. For testing the possibility that it might be due to an element 90 (thorium) or 91 (palladium), we repeated the reaction at least ten times, adding an amount of uranium $X_1 + X_2$ corresponding to about 2,000 impulses per minute; also some cerium and lanthanum were added in order to sustain uranium X. In these conditions the manganese reaction carried only the 13 min.-activity; no trace of the 2,000 impulses of uranium X_1 (period 24 days) was found in the precipitate; and none of uranium X_2, although the operation had been performed in less than two minutes from the precipitation of the manganese dioxide, so that several hundreds of impulses of uranium X_2 (period 75 sec.) would have been easily recognisable.

Similar evidence was obtained for excluding atomic numbers 88 (radium) and 89 (actinium). For this, mesothorium-1 and -2 were used, adding barium and lanthanum; the evidence was completely negative, as in the former case. The eventual precipitation of uranium-X_1 and mesothorium-1, which do not emit β-rays penetrating enough to be detectable in our counters, would have been revealed by the subsequent formation respectively of uranium-X_2 and mesothorium-2.

Lastly, we added to the irradiated uranium solution some inactive lead and bismuth, and proved that the conditions of the manganese dioxide reaction could be regulated in such a way as to obtain the precipitation of manganese dioxide with the 13 min.-activity, without carrying down lead and bismuth.

In this way it appears that we have excluded the possibility that the 13 min.-activity is due to isotopes of uranium (92), palladium (91), thorium (90), actinium (89), radium (88), bismuth (83), lead (82). Its behaviour excludes also ekacæsium (87) and emanation (86).

This negative evidence about the identity of the 13 min.-activity from a large number of heavy elements suggests the possibility that the atomic number of the element may be greater than 92. If it were an element 93, it would be chemically homologous with manganese and rhenium. This hypothesis is supported to some extent also by the observed fact that the 13 min.-activity is carried down by a precipitate of rhenium sulphide insoluble in hydrochloric acid. However, as several elements are easily precipitated in this form, this evidence cannot be considered as very strong.

The possibility of an atomic number 94 or 95 is not easy to distinguish from the former, as the chemical properties are probably rather similar. Valuable information on the processes involved could be gathered by an investigation of the possible emission of heavy particles. A careful search for such heavy particles has not yet been carried out, as they require for their observation that the active product should be in the form of a very thin layer. It seems therefore at present premature to form any definite hypothesis on the chain of disintegrations involved.

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

1. Grundannahmen der Theorie.

Bei dem Versuch, eine Theorie der Kernelektronen sowie der β-Emission aufzubauen, begegnet man bekanntlich zwei Schwierigkeiten. Die erste ist durch das kontinuierliche β-Strahlenspektrum bedingt. Falls der Erhaltungssatz der Energie gültig bleiben soll, muß man annehmen, daß ein Bruchteil der beim β-Zerfall frei werdenden Energie unseren bisherigen Beobachtungsmöglichkeiten entgeht. Nach dem Vorschlag von W. Pauli kann man z. B. annehmen, daß beim β-Zerfall nicht nur ein Elektron, sondern auch ein neues Teilchen, das sogenannte „Neutrino" (Masse von der Großenordnung oder kleiner als die Elektronenmasse; keine elektrische Ladung) emittiert wird. In der vorliegenden Theorie werden wir die Hypothese des Neutrinos zugrunde legen.

Eine weitere Schwierigkeit für die Theorie der Kernelektronen besteht darin, daß die jetzigen relativistischen Theorien der leichten Teilchen (Elektronen oder Neutrinos) nicht imstande sind, in einwandfreier Weise zu erklären, wie solche Teilchen in Bahnen von Kerndimensionen gebunden werden können.

Es scheint deswegen zweckmäßiger, mit Heisenberg[2]) anzunehmen, daß ein Kern nur aus schweren Teilchen, Protonen und Neutronen, besteht. Um trotzdem die Möglichkeit der β-Emission zu verstehen, wollen wir versuchen, eine Theorie der Emission leichter Teilchen aus einem Kern in Analogie zur Theorie der Emission eines Lichtquants aus einem angeregten Atom beim gewöhnlichen Strahlungsprozeß aufzubauen. In der Strahlungstheorie ist die totale Anzahl der Lichtquanten keine Konstante: Lichtquanten entstehen, wenn sie von einem Atom emittiert werden, und verschwinden, wenn sie absorbiert werden. In Analogie hierzu wollen wir der β-Strahlentheorie folgende Annahmen zugrunde legen:

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[1]) Vgl. die vorläufige Mitteilung: La Ricerca Scientifica **2**, Heft 12, 1933. — [2]) W. Heisenberg, ZS. f. Phys. **77**, 1, 1932.

a) Die totale Anzahl der Elektronen, sowie der Neutrinos, ist nicht notwendigerweise konstant. Elektronen (oder Neutrinos) können entstehen und verschwinden. Diese Möglichkeit hat jedoch keine Analogie zum Entstehen oder Verschwinden eines Paares aus einem Elektron und einem Positron; falls man das Positron als Diracsches „Loch" interpretiert, kann man in der Tat diesen letzten Prozeß einfach als einen Quantensprung eines Elektrons zwischen einem Zustand mit negativer Energie und einem Zustand mit positiver Energie mit Erhaltung der totalen (unendlich großen) Anzahl der Elektronen auffassen.

b) Die schweren Teilchen, Neutronen und Protonen, können wie bei Heisenberg als zwei innere Quantenzustände des schweren Teilchens betrachtet werden. Wir formulieren dies durch die Einführung einer inneren Koordinate ϱ des schweren Teilchens, welche nur zwei Werte annehmen kann: $\varrho = 1$, falls das Teilchen ein Neutron ist; $\varrho = -1$, falls das Teilchen ein Proton ist.

c) Die Hamilton-Funktion des aus schweren und leichten Teilchen bestehenden Systems muß so gewählt werden, daß jedem Übergang von Neutron zu Proton das Entstehen eines Elektrons und eines Neutrinos zugeordnet ist. Dem umgekehrten Prozeß, Verwandlung eines Protons in ein Neutron, soll dagegen das Verschwinden eines Elektrons und eines Neutrinos zugeordnet sein. Man bemerke, daß hierdurch die Erhaltung der Ladung gesichert ist.

2. *Die in der Theorie auftretenden Operatoren.*

Ein mathematischer Formalismus der Theorie in Einklang mit diesen drei Forderungen kann am leichtesten mit Hilfe der Dirac-Jordan-Kleinschen Methode[1]) der „zweiten Quantelung" aufgebaut werden. Wir werden also die Wahrscheinlichkeitsamplituden ψ und φ der Elektronen und der Neutrinos sowie die komplex konjugierten Größen ψ^* und φ^* als Operatoren auffassen; für die Beschreibung der schweren Teilchen werden wir dagegen die übliche Darstellung im Konfigurationsraum benutzen, wobei natürlich auch ϱ als Koordinate mitgezählt werden muß.

Wir führen zuerst zwei Operatoren Q und Q^* ein, welche auf die Funktionen der zweiwertigen Variablen ϱ als die linearen Substitutionen

$$Q = \begin{vmatrix} 0 & 1 \\ 0 & 0 \end{vmatrix}; \quad Q^* = \begin{vmatrix} 0 & 0 \\ 1 & 0 \end{vmatrix} \tag{1}$$

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[1]) Vgl. z. B. P. Jordan u. O. Klein, ZS. f. Phys. **45**, 751, 1927; W. Heisenberg, Ann. d. Phys. **10**, 888, 1931.

wirken. Man sieht ohne weiteres, daß Q einem Übergang von Proton zu Neutron entspricht und Q^* einem Übergang von Neutron zu Proton.

Die Bedeutung der als Operatoren aufgefaßten Wahrscheinlichkeitsamplituden ψ und φ ist bekanntlich die folgende: Sei

$$\psi_1 \psi_2 \ldots \psi_s \ldots$$

ein System individueller Quantenzustände für die Elektronen. Man setze weiter

$$\psi = \sum_s \psi_s a_s; \quad \psi^* = \sum_s \psi_s^* a_s^*. \tag{2}$$

Die Amplituden a_s und die komplex konjugierten Größen a_s^* sind Operatoren, welche auf die Funktionen der Besetzungszahlen $N_1, N_2, \ldots, N_s, \ldots$ der individuellen Quantenzustände wirken. Im Falle des Pauli-Prinzips ist jedes der N_s nur der beiden Werte 0 und 1 fähig. Die Operatoren a_s und a_s^* sind dann folgendermaßen definiert:

$$\left.\begin{aligned} a_s \Psi(N_1 N_2 \ldots N_s \ldots) &= (-1)^{N_1+N_2+\cdots+N_s-1}(1-N_s)\Psi(N_1 N_2 \ldots 1-N_s \ldots) \\ a_s^* \Psi(N_1 N_2 \ldots N_s \ldots) &= (-1)^{N_1+N_2+\cdots+N_s-1} N_s \Psi(N_1 N_2 \ldots 1-N_s \ldots) \end{aligned}\right\} . \tag{3}$$

Der Operator a_s^* entspricht der Erzeugung und der Operator a_s dem Verschwinden eines Elektrons im Quantenzustand s.

Entsprechend zu (2) setze man für die Neutrinos

$$\varphi = \sum_\sigma \varphi_\sigma b_\sigma \quad \varphi^* = \sum_\sigma \varphi_\sigma^* b_\sigma^*. \tag{4}$$

Die komplex-konjugierten Größen b_σ und b_σ^* sind Operatoren, die auf die Funktionen der Besetzungszahlen $M_1, M_2, \ldots, M_\sigma, \ldots$ der individuellen Quantenzustände $\varphi_1, \varphi_2, \ldots, \varphi_\sigma, \ldots$ der Neutrinos wirken. Nimmt man an, daß auch für die Neutrinos das Pauli-Prinzip gilt, so sind die Zahlen M_σ nur der beiden Werte 0 und 1 fähig. Es ist ferner:

$$\left.\begin{aligned} b_\sigma \Phi(M_1 M_2 \ldots M_\sigma \ldots) &= (-1)^{M_1+M_2+\cdots+M_\sigma-1}(1-M_\sigma)\Phi(M_1 M_2 \ldots 1-M_\sigma \ldots) \\ b_\sigma^* \Phi(M_1 M_2 \ldots M_\sigma \ldots) &= (-1)^{M_1+M_2+\cdots+M_\sigma-1} M_\sigma \Phi(M_1 M_2 \ldots 1-M_\sigma \ldots) \end{aligned}\right\} . \tag{5}$$

Die Operatoren b_σ und b_σ^* entsprechen dem Verschwinden bzw. dem Entstehen eines Neutrinos im Quantenzustand σ.

3. *Aufstellung der Hamilton-Funktion.*

Die Energie des gesamten, aus schweren und leichten Teilchen bestehenden, Systems ist die Summe der Energien H_{schwer} der schweren Teilchen $+ H_{\text{leicht}}$ der leichten Teilchen $+$ der Wechselwirkungsenergie H zwischen schweren und leichten Teilchen.

Das erste Glied schreiben wir, indem wir vorläufig nur ein einziges schweres Teilchen betrachten, in der Form

$$H_{\text{schwer}} = \frac{1+\varrho}{2} N + \frac{1-\varrho}{2} P, \tag{6}$$

wo N und P die Energieoperatoren des Neutrons bzw. des Protons darstellen. Fur $\varrho = 1$ (Neutron) reduziert sich in der Tat (6) auf N; fur $\varrho = -1$ (Proton) reduziert sich (6) auf P.

Die Energie H_{leicht} der leichten Teilchen nimmt die einfachste Form an, wenn man als Quantenzustände $\psi_1 \psi_2 \ldots \psi_s \ldots$ und $\varphi_1 \varphi_2 \ldots \varphi_\sigma \ldots$ stationäre Zustände fur die Elektronen bzw. die Neutrinos nimmt. Fur die Elektronen soll man dabei etwa die stationären Zustande im Coulomb-Feld des Kerns, unter Berucksichtigung der Elektronenabschirmung, wahlen. Fur die Neutrinos kann man einfach ebene de Broglie-Wellen annehmen, da wohl die auf die Neutrinos wirkenden Kräfte keine wesentliche Rolle spielen. Seien $H_1 H_2 \ldots H_s \ldots$ und $K_1 K_2 \ldots K_\sigma \ldots$ die Energien der stationären Zustände der Elektronen und der Neutrinos; dann haben wir:

$$H_{\text{leicht}} = \sum_s H_s N_s + \sum_\sigma K_\sigma M_\sigma. \tag{7}$$

Es bleibt nur noch die Wechselwirkungsenergie zu schreiben. Diese besteht erstens aus der Coulomb-Energie zwischen Proton und Elektronen; bei schweren Kernen spielt jedoch die Anziehung durch ein einziges Proton nur eine untergeordnete Rolle[1]) und trägt in keinem Falle zum Prozeß des β-Zerfalls bei. Wir wollen also dies Glied der Einfachheit halber nicht berucksichtigen. Wir mussen hingegen zur Hamilton-Funktion ein Glied addieren, das die Bedingung c) von Ziffer 1 erfullt.

Ein Glied, das notwendigerweise die Verwandlung eines Protons in ein Neutron mit dem Verschwinden eines Elektrons und eines Neutrinos koppelt, hat nun nach Ziffer 2 die Form

$$Q\, a_s\, b_\sigma. \tag{8}$$

Der komplex konjugierte Operator

$$Q^*\, a_s^*\, b_\sigma^* \tag{8'}$$

koppelt dagegen die umgekehrten Prozesse (Verwandlung eines Neutrons in ein Proton und Entstehen eines Elektrons und eines Neutrinos).

Ein Wechselwirkungsglied, das die Bedingung c) erfullt, kann also in der folgenden Form geschrieben werden:

$$H = Q \sum_{s\sigma} c_{s\sigma}\, a_s\, b_\sigma + Q^* \sum_{s\sigma} c_{s\sigma}^*\, a_s^*\, b_\sigma^*, \tag{9}$$

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[1]) Die Coulombsche Wirkung der zahlreichen übrigen Protonen muß natürlich als statisches Feld in Betracht gezogen werden.

wo $c_{s\,u}$ und $c^*_{s\,u}$ Größen darstellen, die von den Koordinaten, Impulsen usw. des schweren Teilchens abhängen können.

Zur näheren Bestimmung von H ist man auf Einfachheitskriterien angewiesen. Eine wesentliche Einschränkung in der Freiheit der Wahl von H ist durch die Erhaltung des Impulses sowie durch die Bedingung gesetzt, daß bei einer Drehung oder einer Translation der Raumkoordinaten (9) invariant bleiben muß.

Sehen wir zunächst von den Relativitätskorrektionen und der Spinwirkung ab, so ist wohl die eintachst mögliche Wahl von (9) die folgende:

$$H = g\left\{Q\,\psi(x)\,\varphi(x) + Q^*\,\psi^*(x)\,\varphi^*(x)\right\}, \tag{10}$$

wo g eine Konstante mit den Dimensionen $L^5 M T^{-2}$ darstellt; x repräsentiert die Koordinaten des schweren Teilchens; ψ, φ, ψ^*, φ^* sind durch (2) und (4) gegeben und sind an dem Orte x, y, z des schweren Teilchens zu nehmen.

(10) stellt keineswegs die einzig mögliche Wahl von H dar. Jeder skalare Ausdruck, wie etwa

$$L(p)\,\psi(x)\,M(p)\,\varphi(x)\,N(p) + \text{kompl. konjug.},$$

wo $L(p)$, $M(p)$, $N(p)$ passende Funktionen des Impulses des schweren Teilchens darstellen, wurde ebensogut möglich sein. Da jedoch die Folgerungen aus (10) bisher mit der Erfahrung in Einklang zu sein scheinen, ist es wohl besser, sich vorläufig auf die einfachste Wahl zu beschränken.

Wesentlich ist es jedoch, den Ausdruck (10) derart zu verallgemeinern, daß man mindestens die leichten Teilchen relativistisch behandeln kann. Auch bei dieser Verallgemeinerung ist natürlich eine gewisse Willkür nicht auszuschließen. Die einfachste Lösung des Problems dürfte die folgende sein:

Relativistisch treten an Stelle von ψ und φ je vier Diracsche Funktionen $\psi_1\psi_2\psi_3\psi_4$ und $\varphi_1\varphi_2\varphi_3\varphi_4$. Wir betrachten nun die 16 unabhängigen bilinearen Kombinationen aus $\psi_1\psi_2\psi_3\psi_4$ und $\varphi_1\varphi_2\varphi_3\varphi_4$. Bei einer Lorentz-Transformation der Koordinaten erfahren diese 16 Größen eine lineare Transformation, eine Darstellung der Ordnung 16 der Lorentz-Gruppe. Diese Darstellung spaltet sich in verschiedene einfachere Darstellungen; im besonderen transformieren sich die vier bilinearen Kombinationen:

$$\left.\begin{aligned}
A_0 &= -\psi_1\varphi_2 + \psi_2\varphi_1 + \psi_3\varphi_4 - \psi_4\varphi_3,\\
A_1 &= \psi_1\varphi_3 - \psi_2\varphi_4 - \psi_3\varphi_1 + \psi_4\varphi_2,\\
A_2 &= i\psi_1\varphi_3 + i\psi_2\varphi_4 - i\psi_3\varphi_1 - i\psi_4\varphi_2,\\
A_3 &= -\psi_1\varphi_4 - \psi_2\varphi_3 + \psi_3\varphi_2 + \psi_4\varphi_1,
\end{aligned}\right\} \tag{11}$$

wie die Komponenten eines polaren Vierervektors, also wie die Komponenten des elektromagnetischen Viererpotentials. Es liegt nun nahe, die Größen

$$g\,(Q A_i + Q^* A_i^*)$$

in der Hamilton-Funktion des schweren Teilchens in einer Stellung aufzunehmen, die der Stellung der Komponenten des Viererpotentials entspricht.

Hier begegnen wir einer Schwierigkeit, welche davon herrührt, daß die relativistische Wellengleichung für die schweren Teilchen unbekannt ist. Falls die Geschwindigkeit des schweren Teilchens klein gegenuber c ist, kann man sich jedoch auf den zu eV (V = skalares Potential) analogen Term beschränken und schreiben:

$$\begin{aligned} H = g\,[Q\,(&- \psi_1 \varphi_2 + \psi_2 \varphi_1 + \psi_3 \varphi_4 - \psi_4 \varphi_3) \\ &+ Q^*\,(- \psi_1^* \varphi_2^* + \psi_2^* \varphi_1^* + \psi_3^* \varphi_4^* - \psi_4^* \varphi_3^*)]. \end{aligned} \tag{12}$$

Zu diesem Glied sollen noch andere Glieder von der Größenordnung v/c addiert werden. Da die Geschwindigkeiten der Neutronen und Protonen in den Kernen gewöhnlich klein gegenüber der Lichtgeschwindigkeit sind, wollen wir diese Glieder vorläufig vernachlässigen (vgl. hierzu Ziffer 9).

(12) kann in symbolischer Schreibweise folgendermaßen abgekürzt werden:

$$H = g\,[Q\,\tilde{\psi}^*\,\delta\,\varphi + Q^*\,\tilde{\psi}\,\delta\,\varphi^*], \tag{13}$$

wo ψ und φ als vertikale Matrixspalten zu schreiben sind; das Zeichen $\sim$ verwandelt eine Matrix in die konjugiert transponierte; und es ist

$$\delta = \begin{vmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{vmatrix} \tag{14}$$

Mit diesen Bezeichnungen bekommt man durch Vergleich mit (9)

$$c_{s\sigma} = g\,\tilde{\psi}_s^*\,\delta\,\varphi_\sigma; \qquad c_{s\sigma}^* = g\,\tilde{\psi}_s\,\delta\,\varphi_\sigma^*, \tag{15}$$

wo ψ_s und φ_s die normierten vierkomponentigen Eigenfunktionen der Zustände s (des Elektrons) und σ (des Neutrinos) darstellen. ψ und φ sind in (15) an der Stelle des schweren Teilchens, also als Funktionen von x, y, z, zu nehmen.

4. *Die Störungsmatrix.*

Die Theorie des β-Zerfalls kann mit Hilfe der aufgestellten Hamilton-Funktion in voller Analogie zur Strahlungstheorie durchgefuhrt werden. In dieser letzteren besteht die Hamilton-Funktion bekanntlich aus der

Summe: Energie des Atoms + Energie des reinen Strahlungsfeldes + Kopplungsenergie. Dies letzte Glied wird als Störung der beiden anderen aufgefaßt. In Analogie hierzu werden wir in unserem Falle die Summe

$$H_{\text{schwer}} + H_{\text{leicht}} \tag{16}$$

als ungestörte Hamilton-Funktion betrachten; hinzu kommt die durch das Kopplungsglied (13) dargestellte Störung.

Die Quantenzustände des ungestörten Systems können folgendermaßen numeriert werden:

$$(\varrho, n, N_1 N_2 \dots N_s \dots M_1 M_2 \dots M_\sigma \dots), \tag{17}$$

wo die erste Zahl ϱ einen der beiden Werte ± 1 annimmt und angibt, ob das schwere Teilchen ein Neutron oder ein Proton ist. Die zweite Zahl n numeriert den Quantenzustand des Neutrons oder des Protons. Für $\varrho = 1$ (Neutron) sei die entsprechende Eigenfunktion

$$u_n(x), \tag{18}$$

wo x die Koordinaten des schweren Teilchens, bis auf ϱ, darstellt. Für $\varrho = -1$ (Proton) sei die Eigenfunktion

$$v_n(x). \tag{19}$$

Die übrigen Zahlen $N_1 N_2 \dots N_s \dots M_1 M_2 \dots M_\sigma \dots$ sind nur der beiden Werte 0 und 1 fähig und geben an, ob der betreffende Zustand des Elektrons oder des Neutrinos besetzt ist.

Faßt man nun die allgemeine Form (9) der Störungsenergie ins Auge, so sieht man, daß sie von Null verschiedene Elemente nur fur solche Übergänge hat, bei denen entweder das schwere Teilchen von einem Neutron in einen Protonenzustand übergeht und zugleich ein Elektron und ein Neutrino entstehen, oder umgekehrt.

Mit Hilfe von (1), (3), (5), (9), (18), (19) findet man ohne weiteres das betreffende Matrixelement

$$H^{1\, n\, N_1 N_2 \dots 0_s \dots M_1 M_2 \dots 0_\sigma \dots}_{-1\, m\, N_1 N_2 \dots 1_s \dots M_1 M_2 \dots 1_\sigma \dots} = \pm \int v_m^* c_{s\sigma}^* u_n \, d\tau, \tag{20}$$

wo die Integration über den Konfigurationsraum des schweren Teilchens (bis auf die Koordinate ϱ) erstreckt werden muß. Das $\pm$-Zeichen bedeutet genauer

$$(-1)^{N_1 + N_2 + \dots + N_{s-1} + M_1 + M_2 + \dots + M_{\sigma-1}}$$

und wird übrigens aus den folgenden Rechnungen herausfallen. Dem entgegengesetzten Übergang entspricht ein komplex konjugiertes Matrixelement.

Fuhrt man für $c^*_{s\sigma}$ den Wert (15) ein, so erhält man

$$H^{1\,n\,0_s\,0_\sigma}_{-1\,m\,1_s\,1_\sigma} = \pm g \int v^*_m u_n \widetilde{\psi}_s \delta \varphi^*_\sigma \, d\tau, \tag{21}$$

wo der Kürze wegen im ersten Glied alle gleichbleibenden Indizes fortgelassen worden sind.

5. *Theorie des β-Zerfalls.*

Ein β-Zerfall besteht in einem Prozeß, bei welchem ein Kernneutron sich in ein Proton verwandelt und gleichzeitig mit dem geschilderten Mechanismus ein Elektron, das als β-Strahl beobachtet wird und ein Neutrino emittiert werden. Um die Wahrscheinlichkeit dieses Prozesses zu berechnen, wollen wir annehmen, daß zur Zeit $t = 0$ ein Neutron in einem Kernzustand mit Eigenfunktion $u_n(x)$ vorhanden ist und $N_s = M_\sigma = 0$, d. h. der Elektronenzustand s und der Neutrinozustand σ leer sind. Dann ist für $t = 0$ die Wahrscheinlichkeitsamplitude des Zustands $(1, n, 0_s, 0_\sigma)$

$$a_{1\,n\,0_s\,0_\sigma} = 1 \tag{22}$$

und die des Zustandes $(-1, m, 1_s, 1_\sigma)$, wo das Neutron in ein Proton mit der Eigenfunktion $v_m(x)$ unter Emission eines Elektrons und eines Neutrinos übergegangen ist, gleich Null.

Mit Anwendung der gewöhnlichen Störungsformeln hat man nun für eine Zeit, die kurz genug ist, damit (22) noch angenähert gültig ist:

$$\dot{a}_{-1\,m\,1_s\,1_\sigma} = -\frac{2\pi i}{h} H^{1\,n\,0_s\,0_\sigma}_{-1\,m\,1_s\,1_\sigma} e^{\frac{2\pi i}{h}(-W + H_s + K_\sigma)t}, \tag{23}$$

wo W die Energiedifferenz des Neutronen- und des Protonenzustandes darstellt.

Aus (23) erhält man (da für $t = 0$, $a_{-1\,m\,1_s\,1_\sigma} = 0$)

$$a_{-1\,m\,1_s\,1_\sigma} = -H^{1\,n\,0_s\,0_\sigma}_{-1\,m\,1_s\,1_\sigma} \frac{e^{\frac{2\pi i}{h}(-W + H_s + K_\sigma)t} - 1}{-W + H_s + K_\sigma}. \tag{24}$$

Die Wahrscheinlichkeit des betrachteten Übergangs ist also zur Zeit t

$$|a_{-1\,m\,1_s\,1_\sigma}|^2 = 4 \left| H^{1\,n\,0_s\,0_\sigma}_{-1\,m\,1_s\,1_\sigma} \right|^2 \frac{\sin^2 \frac{\pi t}{h}(-W + H_s + K_\sigma)}{(-W + H_s + K_\sigma)^2}. \tag{25}$$

Um die Lebensdauer des Neutronenzustands u_n zu berechnen, hat man den Ausdruck (25) über alle freien Elektronen- und Neutrinozustände zu summieren.

Eine wesentliche Vereinfachung in der Ausfuhrung der Summe erhält man durch die Bemerkung, daß die de Broglie-Wellenlänge fur Elektronen und Neutrinos mit Energien von einigen Millionen Volt wesentlich großer ist als die Kerndimensionen. In erster Näherung kann man also die Eigenfunktionen ψ_s und φ_σ innerhalb des Kerns als Konstante betrachten. (21) wird dann:

$$H^{1\,n\,0_s\,0_\sigma}_{-1\,m\,1_s\,1_\sigma} = \pm\, g\, \tilde{\psi}_s\, \delta\, \varphi_\sigma^* \int v_m^*\, u_n\, \mathrm{d}\tau, \tag{26}$$

wobei hier und im folgenden ψ_s und φ_σ an der Stelle des Kerns zu nehmen sind (vgl. Ziffer 8). Aus (26) hat man

$$\left|H^{1\,n\,0_s\,0_\sigma}_{-1\,m\,1_s\,1_\sigma}\right|^2 = g^2 \left|\int v_m^*\, u_n\, \mathrm{d}\tau\right|^2 \tilde{\psi}_s\, \delta\, \varphi_\sigma^*\, \tilde{\varphi}_\sigma^*\, \tilde{\delta}\, \psi_s. \tag{27}$$

Die Zustände σ des Neutrinos sind durch ihren Impuls p_σ und die Spinrichtung bestimmt. Falls wir zu Normierungszwecken in einem Volumen Ω quantisieren, dessen Dimensionen wir nachher ins Unendliche wachsen lassen werden, so sind die normierten Neutrinoeigenfunktionen ebene Dirac-Wellen, mit der Dichte $1/\Omega$. Eine einfache Algebra erlaubt dann in (27) den Mittelwert uber alle Richtungen von p_σ und alle Spinrichtungen des Neutrinos zu nehmen. (Zu betrachten sind dabei nur die positiven Eigenwerte; die negativen sind mit einem der Diracschen Lochertheorie analogen Kunstgriff zu beseitigen.) Man findet:

$$\overline{\left|H^{1\,n\,0_s\,0_\sigma}_{-1\,m\,1_s\,1_\sigma}\right|^2} = \frac{g^2}{4\,\Omega} \left|\int v_m^*\, u_n\, \mathrm{d}\tau\right|^2 \left(\tilde{\psi}_s\, \psi_s - \frac{\mu\, c^2}{K_\sigma}\, \tilde{\psi}_s \beta\, \psi_s\right), \tag{28}$$

wo μ die Ruhemasse des Neutrinos und β die Diracsche Matrix

$$\beta = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{vmatrix} \tag{29}$$

darstellt. Beachtet man nun:

daß die Anzahl der Neutrinozustände positiver Energie mit Impuls zwischen p_σ und $p_\sigma + \mathrm{d}p_\sigma$ $\dfrac{8\pi\Omega}{h^3}\, p_\sigma^2\, \mathrm{d}p_\sigma$ ist;

daß $\dfrac{\partial K_\sigma}{\partial p_\sigma} = v_\sigma$, wo v_σ die Geschwindigkeit des Neutrinos im Zustand σ darstellt;

daß (25) ein scharfes Maximum in der Nähe des Wertes von p_σ hat, fur den die Variation der ungestörten Energie verschwindet, d. h.

$$-W + H_s + K_\sigma = 0, \tag{30}$$

so kann man die Summe von (25) uber σ in bekannter Weise[1]) ausfuhren, und man findet:

$$t \cdot \frac{8\,\pi^3 g^2}{h^4} \left| \int v_m^* u_n \,d\,\tau \right|^2 \frac{p_\sigma^2}{v_\sigma} \left(\widetilde{\psi}_s \psi_s - \frac{\mu c^2}{K_\sigma} \widetilde{\psi}_s \beta \psi_s \right), \tag{31}$$

wo p_σ hier den Wert des Neutrinoimpulses bedeutet, fur den (30) gultig ist.

6. *Bestimmungsstucke der Übergangswahrscheinlichkeit.*

(31) gibt die Wahrscheinlichkeit dafur an, daß während der Zeit t ein β-Zerfall mit Übergang des Elektrons in den Zustand s stattfindet. Wie es sein soll, ist diese Wahrscheinlichkeit proportional der Zeit t (t ist als klein in bezug auf die Lebensdauer angenommen worden); der Koeffizient von t gibt die Übergangswahrscheinlichkeit fur den geschilderten Prozeß an. Sie ist:

$$P_s = \frac{8\,\pi^3 g^2}{h^4} \left| \int v_m^* u_n \,d\,\tau \right|^2 \frac{p_\sigma^2}{v_\sigma} \left(\widetilde{\psi}_s \psi_s - \frac{\mu c^2}{K_\sigma} \widetilde{\psi}_s \beta \psi_s \right). \tag{32}$$

Man bemerke:

a) Fur die freien Neutrinozustände ist immer $K_\sigma > \mu c^2$. Damit (30) befriedigt werden kann, ist also notwendig, daß

$$H_s \leqq W - \mu c^2. \tag{33}$$

Dem $=$-Zeichen entspricht die obere Grenze des kontinuierlichen β-Strahlspektrums.

b) Da fur die freien Elektronenzustände $H_s > mc^2$ ist, bekommt man die folgende, fur die Moglichkeit des β-Zerfalls notwendige Bedingung

$$W \geqq (m + \mu)\, c^2. \tag{34}$$

Ein besetzter Neutronenzustand n im Kerne muß also hoch genug uber einem unbesetzten Protonenzustand m liegen, damit der β-Prozeß vor sich gehen kann.

c) Nach (32) hängt P_s von den Eigenfunktionen u_n, v_m des schweren Teilchens im Kerne durch das Matrixelement

$$Q_{m\,n}^* = \int v_m^* u_n \,d\,\tau \tag{35}$$

ab. Dies Matrixelement spielt in der β-Strahltheorie eine ähnliche Rolle wie das Matrixelement des elektrischen Moments eines Atoms in der Strahlungstheorie. Das Matrixelement (35) hat normalerweise die Größenordnung 1; durch besondere Symmetrieeigenschaften von u_n und v_m kann es jedoch oft vorkommen, daß Q_{mn}^* verschwindet. In solchen Fällen sprechen

1) Fur die genaue Beschreibung der Methode, solche Summen auszufuhren. vgl. irgendeinen Aufsatz uber Strahlungstheorie; etwa: E. Fermi, Rev. Mod. Phys. 4, 87, 1932.

wir von *verbotenen β-Übergängen.* Man muß natürlich nicht erwarten, daß die verbotenen Übergänge überhaupt nicht vorkommen, da (32) nur eine Näherungsformel ist. Wir werden in Ziffer 9 etwas über diesen Typ von Übergängen sprechen.

7. *Die Masse des Neutrinos.*

Durch die Übergangswahrscheinlichkeit (32) ist die Form des kontinuierlichen β-Spektrums bestimmt. Wir wollen zuerst diskutieren, wie diese Form von der Ruhemasse μ des Neutrinos abhängt, um von einem Vergleich mit den empirischen Kurven diese Konstante zu bestimmen. Die Masse μ ist in dem Faktor p_σ^2/v_σ enthalten. Die Abhängigkeit der Form der Energieverteilungskurve von μ ist am meisten ausgeprägt in der Nähe des Endpunktes der Verteilungskurve. Ist E_0 die Grenzenergie der β-Strahlen, so sieht man ohne Schwierigkeit, daß die Verteilungskurve für Energien E in der Nähe von E_0 bis auf einen von E unabhängigen Faktor sich wie

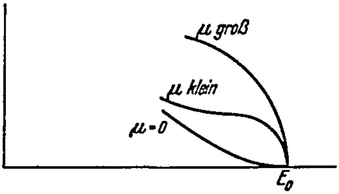

Fig. 1.

$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)} \tag{36}$$

verhält.

In der Fig. 1 ist das Ende der Verteilungskurve für $\mu = 0$ und für einen kleinen und einen großen Wert von μ gezeichnet. Die größte Ähnlichkeit mit den empirischen Kurven zeigt die theoretische Kurve für $\mu = 0$.

Wir kommen also zu dem Schluß, daß die Ruhemasse des Neutrinos entweder Null oder jedenfalls sehr klein in bezug auf die Masse des Elektrons ist[1]). In den folgenden Rechnungen werden wir die einfachste Hypothese $\mu = 0$ einführen. Es wird dann (30)

$$v_\sigma = c; \quad K_\sigma = p_\sigma c; \quad p_\sigma = \frac{K_\sigma}{c} = \frac{W - H_s}{c}. \tag{37}$$

Die Ungleichungen (33), (34) werden jetzt:

$$H_s \leqq W; \quad W \geqq m c^2. \tag{38}$$

Und die Übergangswahrscheinlichkeit (32) nimmt die Form an:

$$P_s = \frac{8\pi^3 g^2}{c^3 h^4}\left|\int v_m^* u_n \, d\tau\right|^2 \tilde{\psi}_s \psi_s (W - H_s)^2. \tag{39}$$

[1]) In einer kürzlich erschienenen Notiz kommt F. Perrin, C. R. **197**, 1625, 1933, mit qualitativen Überlegungen zu demselben Schluß.

8. Lebensdauer und Form der Verteilungskurve für „erlaubte" Übergänge.

Aus (39) kann man eine Formel ableiten, welche angibt, wieviel β-Übergänge in der Zeiteinheit stattfinden, für welche das β-Teilchen einen Impuls zwischen $mc\eta$ und $mc(\eta + d\eta)$ erhält. Dazu muß man eine Formel für die Summe von $\tilde{\psi}_s \psi_s$ am Orte des Kerns über alle im kontinuierlichen Spektrum liegenden Quantenzustände des betreffenden Intervalls ableiten.

Dabei sei bemerkt, daß die relativistischen Eigenfunktionen im Coulomb-Feld für die Zustände mit $j = 1/2$ ($^2s_{1/2}$ und $^2p_{1/2}$) für $r = 0$ unendlich groß werden. Nun gehorcht aber die Kernanziehung für die Elektronen dem Coulombschen Gesetz nur bis $r > \varrho$, wo ϱ hier den Kernradius bedeutet. Eine Überschlagsrechnung zeigt, daß, wenn man plausible Annahmen über den Verlauf des elektrischen Feldes innerhalb des Kerns macht, der Wert von $\tilde{\psi}_s \psi_s$ im Mittelpunkt einen Wert hat, der sehr nahe dem Werte liegt, den $\tilde{\psi}_s \psi_s$ im Falle des Coulomb-Gesetzes in der Entfernung ϱ vom Mittelpunkt annehmen würde.

Durch Heranziehung der bekannten Formeln[1]) für die relativistischen Eigenfunktionen des Kontinuums im wasserstoffähnlichen Falle findet man also nach einer ziemlich langwierigen Rechnung

$$\sum_{d\eta} \tilde{\psi}_s \psi_s = d\eta \cdot \frac{32\pi m^3 c^3}{h^3 [\Gamma(3+2S)]^2} \left(\frac{4\pi m c \varrho}{h}\right)^{2S} \eta^{2+2S} e^{\pi\gamma \frac{\sqrt{1+\eta^2}}{\eta}} \left| \Gamma\left(1+S+i\gamma \frac{\sqrt{1+\eta^2}}{\eta}\right)\right|^2, \quad (40)$$

wo

$$\gamma = Z/137; \quad S = \sqrt{1-\gamma^2} - 1. \quad (41)$$

Die Übergangswahrscheinlichkeit in einen Elektronenzustand mit einem Impuls des Intervalls $mc\,d\eta$ wird dann nach (39):

$$P(\eta)\,d\eta = d\eta \cdot g^2 \frac{256\pi^4}{[\Gamma(3+2S)]^2} \frac{m^5 c^4}{h^7} \left(\frac{4\pi m c \varrho}{h}\right)^{2S} \left| \int v_m^* u_n \, d\tau \right|^2$$

$$\cdot \eta^{2+2S} e^{\pi\gamma \frac{\sqrt{1+\eta^2}}{\eta}} \left| \Gamma\left(1+S+i\gamma \frac{\sqrt{1+\eta^2}}{\eta}\right)\right|^2 \left(\sqrt{1+\eta_0^2} - \sqrt{1+\eta^2}\right)^2, \quad (42)$$

wo η_0 den in Einheiten mc gemessenen maximalen Impuls der emittierten β-Strahlen darstellt.

Die numerische Auswertung von (42) kann man etwa für $\gamma = 0{,}6$, d. h. $Z = 82{,}2$ machen, da ja die Atomnummern der radioaktiven Stoffe nicht weit von diesem Wert liegen. Für $\gamma = 0{,}6$ ist nach (41) $S = -0{,}2$. Man findet weiter, daß für $\eta < 10$ die folgende Formel angenähert gilt:

$$\eta^{1,6} e^{0,6\pi \frac{\sqrt{1+\eta^2}}{\eta}} \left| \Gamma\left(0{,}8 + 0{,}6\, i \frac{\sqrt{1+\eta^2}}{\eta}\right)\right|^2 \cong 4{,}5\,\eta + 1{,}6\,\eta^2. \quad (43)$$

[1]) R. H. Hulme, Proc. Roy. Soc. London (A) 133, 381, 1931.

Formel (42) wird damit, wenn man $\varrho = 9 \cdot 10^{-13}$ setzt:

$$P(\eta)\,d\eta = 1{,}75 \cdot 10^{95} g^2 \left| \int v_m^* u_n \, d\tau \right|^2 (\eta + 0{,}355\,\eta^2)\left(\sqrt{1+\eta_0^2} - \sqrt{1+\eta^2}\right)^2. \quad (44)$$

Die reziproke Lebensdauer erhält man aus (44) durch Integration von $\eta = 0$ bis $\eta = \eta_0$; man findet:

$$\frac{1}{\tau} = 1{,}75 \cdot 10^{95} g^2 \left| \int v_m^* u_n \, d\tau \right|^2 F(\eta_0), \quad (45)$$

wo

$$F(\eta_0) = \frac{2}{3}\left(\sqrt{1+\eta_0^2} - 1\right)$$

$$+ \frac{\eta_0^4}{12} - \frac{\eta_0^2}{3} + 0{,}355\left[-\frac{\eta_0}{4} - \frac{\eta_0^3}{12} + \frac{\eta_0^5}{30} + \frac{\sqrt{1+\eta_0^2}}{4}\log\left(\eta_0 + \sqrt{1+\eta_0^2}\right)\right]. \quad (46)$$

Für kleine Argumente verhält sich $F(\eta_0)$ wie $\eta_0^6/24$; für größere Argumente sind die Werte von F in der folgenden Tabelle zusammengestellt.

Tabelle 1.

η_0	$F(\eta_0)$	η_0	$F(\eta_0)$	η_0	$F(\eta_0)$	η_0	$F(\eta_0)$
0	$\eta_0^6/24$	2	1,2	4	29	6	185
1	0,03	3	7,5	5	80	7	380

9. *Die verbotenen Übergänge.*

Bevor wir zum Vergleich mit der Erfahrung übergehen, wollen wir noch einige Eigenschaften der verbotenen β-Übergänge diskutieren.

Wie schon bemerkt, ist ein Übergang verboten, wenn das zugehörige Matrixelement (35) verschwindet. Falls nun die Darstellung des Kerns mit individuellen Quantenzuständen der Neutronen und der Protonen eine gute Näherung ist, verschwindet immer Q_{mn}^* aus Symmetriegründen, wenn nicht

$$i = i', \quad (47)$$

wo i und i' die Impulsmomente (in Einheiten $h/2\pi$) des Neutronenzustands u_n und des Protonenzustands v_m darstellen. Der Auswahlregel (47) entspricht, falls die individuellen Zustände keine gute Näherung sind, die allgemeinere

$$I = I', \quad (48)$$

wo I und I' die Impulsmomente des Kerns vor und nach dem β-Zerfall bedeuten.

Die Auswahlregeln (47) und (48) sind bei weitem nicht so scharf wie die Auswahlregeln der Optik. Es gibt hauptsächlich zwei Prozesse, wodurch ein Durchbrechen dieser Auswahlregeln möglich ist:

a) Formel (26) ist durch Vernachlässigung der Variationen von ψ_s und φ_σ innerhalb der Kernausdehnung erhalten worden. Falls man aber ψ_s und φ_σ im Bereich des Kerns nicht als Konstante betrachtet, so erhält man die Möglichkeit von β-Übergängen auch in Fällen, wo Q^*_{mn} verschwindet.

Es ist leicht einzusehen, daß die Intensität solcher Übergange zur Intensität der erlaubten Prozesse großenordnungsmäßig im Verhältnis $(\varrho/\lambda)^2$ steht, wo λ die de Broglie-Wellenlänge der leichten Teilchen dargestellt. Man bemerke hierzu, daß, bei gleicher Energie, die kinetische Energie der Elektronen am Orte des Kerns wegen der elektrostatischen Anziehung erheblich großer ist als die der Neutrinos; die größte Wirkung ruhrt also von der Variation von ψ_s her. Eine Abschätzung der Intensität dieser verbotenen Prozesse zeigt, daß sie rund 100mal schwächer sein mussen als die nach (48) erlaubten Übergänge, fur welche β-Teilchen der gleichen Energie emittiert werden.

Ein Merkmal fur verbotene Übergänge dieses Typs könnte man nicht nur in der verhältnismäßig längeren Lebensdauer, sondern auch in der verschiedenen Form der Energieverteilungskurve der β-Strahlen erblicken; man findet nämlich, daß fur diese Übergänge die Verteilungskurve für kleine Energien tiefer liegen muß als im normalen Falle.

b) Eine zweite Möglichkeit von nach (48) verbotenen Übergängen folgt aus der am Ende von Ziffer 3 bemerkten Tatsache, daß, falls man die Geschwindigkeit der schweren Kernbestandteile nicht gegen die Lichtgeschwindigkeit vernachlässigt, zum Wechselwirkungsglied (12) noch weitere von der Größenordnung v/c hinzutreten. Falls man etwa auch für die schweren Teilchen eine relativistische Wellengleichung vom Diracschen Typus annimmt, könnte man z. B. zu (12) Terme wie

$$gQ\,(\alpha_x A_1 + \alpha_y A_2 + \alpha_z A_3) + \text{komplex konjugiert} \tag{49}$$

addieren, wo $\alpha_x \alpha_y \alpha_z$ die Diracschen Matrizen fur das schwere Teilchen bedeuten und A_1, A_2, A_3 die Raumkomponenten des von (11) definierten Vierervektors sind. Das Glied (49) würde zu (12) in demselben Verhältnis stehen wie die Terme eV bzw. $e\,(\alpha, U)$ (V = skalares Potential; U = Vektorpotential) zu der Diracschen Hamilton-Funktion.

Ein Wechselwirkungsglied wie (49) wurde naturlich auch verbotene Übergänge ermöglichen, mit einer relativen Intensität von der Größenordnung $(v/c)^2$ in bezug auf die der erlaubten Übergänge. Dies gibt also eine zweite Moglichkeit fur das Vorhandensein von Übergängen, die etwa 100mal schwächer sind als die normalen.

10. Vergleich mit der Erfahrung.

Formel (45) gibt eine Beziehung zwischen dem maximalen Impuls der emittierten β-Strahlen und der Lebensdauer der β-strahlenden Substanz. In dieser Beziehung tritt zwar noch ein unbekanntes Element auf, nämlich das Integral

$$\int v_m^* u_n \, d\tau, \tag{50}$$

für dessen Auswertung eine Kenntnis der Eigenfunktionen des Protons und des Neutrons im Kern notwendig wäre. Im Falle der erlaubten Übergänge ist jedoch (50) von der Größenordnung 1. Man kann also erwarten, daß das Produkt

$$\tau F(\eta_0) \tag{51}$$

fur alle erlaubten Übergänge dieselbe Größenordnung hat. Falls aber der betreffende Übergang verboten ist, ist die Lebensdauer rund 100mal größer als im normalen Falle und auch das Produkt (51) wird entsprechend größer.

In der Tabelle 2 sind die Produkte (51) für die radioaktiven Elemente zusammengestellt, für welche man genügende Daten über das kontinuierliche β-Spektrum hat.

Tabelle 2.

Element	τ (Stunden)	η_0	$F(\eta_0)$	$\tau F(\eta_0)$
U X_2	0,026	5,4	115	3,0
Ra B	0,64	2,04	1,34	0,9
Th B	15,3	1,37	0,176	2,7
Th C″	0,076	4,4	44	3,3
Ac C″	0,115	3,6	17,6	2,0
Ra C	0,47	7,07	398	190
Ra E	173	3,23	10,5	1800
Th C	2,4	5,2	95	230
Ms Th_2	8,8	6,13	73	640

Aus der Tabelle sind die zwei erwarteten Gruppen ohne weiteres erkennbar; eine solche Einteilung ist übrigens bereits von Sargent[1]) auf empirischem Wege festgestellt worden. Die Werte von η_0 sind aus der genannten Arbeit von Sargent genommen (zum Vergleich bemerke man, daß: $\eta_0 = (H\varrho)_{\max}/1700$). Die von Sargent als nicht zuverlässig angegebenen Werte von η_0 passen nicht besonders gut in die Einteilung: für UX_1 hat man $\tau = 830$; $\eta_0 = 0{,}76$; $F(\eta_0) = 0{,}0065$; $\tau F(\eta_0) = 5{,}4$; dies Element scheint also zur ersten Gruppe zu passen. Für AcB hat man

[1]) B. W. Sargent, Proc. Roy. Soc. London (A) 139, 659, 1933.

die folgenden Daten: $\tau = 0{,}87$; $\eta_0 = 1{,}24$; $F(\eta_0) = 0{,}102$; $\tau F(\eta_0) = 0{,}09$, also ein τF-Wert etwa zehnmal kleiner als die der ersten Gruppe. Für RaD hat man $\tau = 320000$; $\eta_0 = 0{,}38$ (sehr unsicher); $F(\eta_0) = 0{,}00011$; $\tau F(\eta_0) = 35$. RaD liegt also ungefähr in der Mitte zwischen den beiden Gruppen. Ich habe keine Daten über die anderen β-strahlenden Elemente MsTh$_1$, UY, Ac, AcC, UZ, RaC'' gefunden.

Aus den Daten der Tabelle 2 kann man eine, wenn auch sehr grobe, Abschätzung der Konstante g gewinnen. Nimmt man etwa an, daß in den Fällen wo (50) gleich Eins wird, man $\tau F(\eta_0) = 1$ hat (d. h., in Sekunden, $= 3600$), so bekommt man aus (45):

$$g = 4 \cdot 10^{-50}\,\mathrm{cm}^3 \cdot \mathrm{erg}.$$

Dieser Wert gibt natürlich nur die Größenordnung von g.

Zusammenfassend kann man sagen, daß dieser Vergleich von Theorie und Erfahrung eine so gute Übereinstimmung gibt, wie man nur erwarten konnte. Die bei den als experimentell unsicheren Elementen RaD und AcB festgestellten Abweichungen können wohl teilweise durch Ungenauigkeit der Messungen erklärt werden, teilweise auch durch etwas abnorm große aber gar nicht unplausible Schwankungen des Matrixelements (50). Man hat weiter zu bemerken, daß man aus der den β-Zerfall begleitenden γ-Strahlung schließen kann, daß die meisten β-Zerfälle zu verschiedenen Endzuständen des Protons führen können, wodurch wieder Schwankungen in dem $\tau F(\eta_0)$-Wert erklärt werden können.

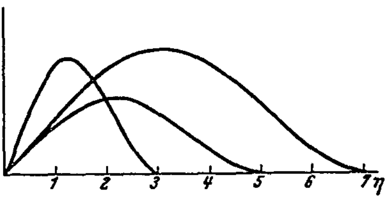

Fig. 2.

Wir wenden uns jetzt zur Frage nach der Form der Geschwindigkeitsverteilungskurve der emittierten β-Strahlen. Für den Fall der erlaubten Übergänge ist die Verteilungskurve als Funktion von η (d. h. bis auf den Faktor 1700, von $H\varrho$) durch (44) gegeben. Verteilungskurven für verschiedene Werte von η_0 sind in der Fig. 2 zusammengestellt, wobei für die Bequemlichkeit der Zeichnung die Ordinateneinheit in den verschiedenen Fällen passend gewählt worden ist. Diese Kurven zeigen eine befriedigende Ähnlichkeit etwa zu den von Sargent[1]) zusammengestellten Verteilungskurven. Nur in dem Teil der Kurve kleiner Energie liegen die Kurven von Sargent etwas tiefer als die theoretischen. Dies ist deutlicher in der

[1]) B. W. Sargent, Proc. Cambridge Phil. Soc. **28**, 538, 1932.

Fig. 3 zu sehen, wo als Abszisse die Energie an Stelle des Impulses genommen worden ist. Hierzu muß man jedoch bemerken, daß die experimentelle Kenntnis des Verteilungsgesetzes für kleine Energien besonders unsicher ist[1]). Übrigens hat man für die verbotenen Übergänge auch theoretisch Kurven zu erwarten, die im Gebiet kleiner Energie tiefer liegen als die der Fig. 2 und 3. Dieser letzte Punkt ist besonders fur den Fall der experimentell verhältnismäßig gut bekannten Kurve des RaE zu beachten. Aus der Tabelle 2 sieht man nämlich, daß RaE einen sehr großen $\tau F(\eta_0)$-Wert hat; der β-Zerfall des RaE ist also gewiß verboten und wird sogar möglicherweise nur erst in zweiter Näherung erlaubt. Ich hoffe in einer nächsten Mitteilung etwas Genaueres uber den Verlauf der Energieverteilungskurven fur die verbotenen Übergänge sagen zu können.

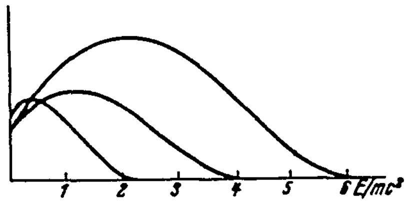

Fig. 3.

Zusammenfassend darf man wohl sagen, daß die Theorie in der hier angegebenen Form in Übereinstimmung mit den allerdings nicht immer besonders genauen experimentellen Daten ist. Sollte man übrigens auch bei einem näheren Vergleich von Theorie und Erfahrung zu Widersprüchen kommen, so wäre es noch moglich, die Theorie abzuändern, ohne ihre begrifflichen Fundamente zu beruhren. Man könnte nämlich Gleichung (9) behalten und eine verschiedene Wahl der $c_{s\sigma}$ treffen. Dies könnte insbesondere zu einer Abänderung der Auswahlregel (48) fuhren und eine andere Form der Energieverteilungskurve sowie der Abhängigkeit der Lebensdauer von der maximalen Energie ergeben. Ob eine solche Änderung notwendig sein wird, kann jedoch erst durch eine weitere Entwicklung der Theorie und möglicherweise auch durch eine Verschärfung der experimentellen Daten gezeigt werden.

[1]) Vgl z. B. E. Rutherford, B. Ellis u. J. Chadwick, Radiations from Radioactive Substances, Cambridge 1932. Siehe insbesondere S. 407.

(Untersuchungen zur Molekularstrahlmethode aus dem Institut für physikalische Chemie der Hamburgischen Universität. Nr. 24.)

Über die magnetische Ablenkung von Wasserstoffmolekülen und das magnetische Moment des Protons. I.

Von **R. Frisch** und **O. Stern** in Hamburg.

Mit 12 Abbildungen. (Eingegangen am 27. Mai 1933.)

Strahlen aus Wasserstoffmolekülen wurden nach der Methode von Gerlach und Stern magnetisch abgelenkt und so ihr magnetisches Moment bestimmt. Die Messungen an Parawasserstoff ergaben das von der Rotation des Moleküls herrührende magnetische Moment zu etwa 1 Kernmagneton ($^1/_{1840}$ Bohrmagneton) pro Rotationsquant. Die Messungen an Orthowasserstoff ergaben das magnetische Moment des Protons zu 2 bis 3 Kernmagnetonen (nicht 1 Kernmagneton, wie bisher vermutet wurde).

In den bisherigen Arbeiten des hiesigen Instituts ist seit jeher[1]) betont worden, daß die Molekularstrahlmethode die Möglichkeit gibt, sehr kleine Momente zu messen, die anderen Methoden nicht zugänglich sind. Den ersten Versuch in dieser Richtung stellt die Arbeit von Knauer und Stern[2]) dar, in der das magnetische Moment des H_2O-Moleküls in der erwarteten Größenordnung ($\sim {}^1/_{1000}$ Bohrmagneton) nachgewiesen wurde. Während aber damals selbst die Messung der Größenordnung nur durch einen besonderen Kunstgriff (Intensitätsmultiplikator) möglich war, gibt die inzwischen erfolgte Entwicklung der Molekularstrahlmethode, insbesondere der Methoden zur Intensitätsmessung[3]), die Möglichkeit einer quantitativen Messung solch kleiner Momente.

Gerade die Untersuchung des H_2 war schon lange beabsichtigt und zwar aus folgenden Gründen. Erstens sollte die Messung bei H_2 *experimentell* besonders gut durchführbar sein: Denn man kann bei Wasserstoff Strahlen von sehr tiefer Temperatur verwenden und damit besonders große Ablenkung erreichen, da die Ablenkung ceteris paribus der absoluten Temperatur umgekehrt proportional ist; außerdem war gerade bei Wasserstoff eine empfindliche und quantitative Meßmethode für die Intensität des Strahles im hiesigen Institut gut durchgearbeitet und vielfach erprobt. Zweitens sind aber die Versuche bei Wasserstoff auch vom *theoretischen*

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[1]) Bereits U. z. M. Nr. 1; O. Stern, ZS. f. Phys. 39, 751, 1926.
[2]) U. z. M. Nr. 3; F. Knauer u. O. Stern, ZS. f. Phys. 39, 780, 1926.
[3]) U. z. M. Nr. 10; F. Knauer u. O. Stern. ZS. f. Phys. 53, 766, 1929; U. z. M. Nr. 14; J. B. Taylor, ebenda 57, 242, 1929.

Standpunkt besonders interessant, namentlich seit der Entdeckung des Ortho- und Parawasserstoffs. Vor allem bietet sich die Möglichkeit einer Messung des magnetischen Moments des Protons, einer Größe, die experimentell bisher nicht zugänglich war, dabei aber ihrer Art nach, als eine Eigenschaft der positiven Elementarladung, besonderes Interesse beansprucht.

Das mechanische Moment des Protons ist mit großer Sicherheit bekannt; es ist gleich dem des Elektrons $= \frac{1}{2} \frac{h}{2\pi}$. Das magnetische Moment des Elektrons ist $2 \frac{e}{2mc} \cdot \frac{1}{2} \cdot \frac{h}{2\pi}$ (ein Bohrmagneton $= 0{,}9 \cdot 10^{-20}$ CGS für ein Elektron bzw. 5600 CGS pro Mol); nimmt man an, daß für das magnetische Moment des Protons dieselbe Formel gilt (eine Annahme, die durch die Diracsche Theorie des Elektrons nahegelegt wird), so würde dieses im Verhältnis der Massen, also 1840mal kleiner sein ($0{,}5 \cdot 10^{-23}$ CGS für ein Proton bzw. 3 CGS pro Mol). Wir wollen diese Größe im folgenden wie bisher (U. z. M. Nr. 1, l. c.) als *ein Kernmagneton* bezeichnen.

Der unmittelbare Zweck der vorliegenden Arbeit war also die Untersuchung des Wasserstoffs mit dem Ziele einer Bestimmung des Protonenmoments. Darüber hinaus aber sollte ganz allgemein eine Apparatur zur Messung von magnetischen Momenten von der Größenordnung Kernmagneton entwickelt werden. In erster Linie sind Messungen von magnetischen Kernmomenten für Fragen der Kernstruktur von Wichtigkeit und könnten die Bestimmungen aus der Hyperfeinstruktur der Spektrallinien kontrollieren und ergänzen. Außerdem gibt es noch andere Fälle, wo Momente dieser Größenordnung auftreten, z. B. bei der Rotation von Molekülen, diamagnetische Momente usw.

Experimentelle Anordnung. Die experimentelle Anordnung war die übliche bei der magnetischen Ablenkung von Molekularstrahlen, nur mußte infolge des kleinen magnetischen Moments der Strahl sehr lang und schmal gemacht werden, und die Inhomogenität recht groß, also auch die Höhe des Strahles sehr klein, um gut meßbare Ablenkungen zu erhalten. Fig. 1 gibt einen schematischen Überblick über die Anordnung. Die Gesamtlänge des Strahles betrug etwa 30 cm, und zwar die Entfernung vom Ofenspalt zum Abbildespalt knapp 15 cm, die Länge des Feldes 10 cm und der Abstand des Auffängerspaltes vom Feldende 5 cm. Die Polschuhe zur Erzeugung des inhomogenen Feldes hatten die übliche Schneide-Furcheform; die Breite der Furche war 1 mm, der Abstand der Schneide von der Furchenebene 0,5 mm. Sie erzeugten eine Inhomogenität $\partial H / \partial s$ von etwa $2{,}2 \cdot 10^5$ Gauß pro Zentimeter.

Aus diesen Daten berechnet sich die Ablenkung nach der Formel:

$$s_\alpha = \frac{1}{2} g t^2 = \frac{1}{2} \frac{\mathfrak{M}}{M} \frac{\partial H}{\partial s} \frac{l^2}{\alpha^2} = \frac{\mathfrak{M}}{4RT} \frac{\partial H}{\partial s} l^2 \begin{pmatrix} \mathfrak{M} = 3\,CGS \\ R = 8{,}3 \cdot 10^{-7} \\ l^2 = 200 \end{pmatrix}.$$

Bei einer Strahltemperatur von 90° abs. beträgt für Moleküle mit der wahrscheinlichsten Geschwindigkeit α die Ablenkung 0,044 mm für ein Kernmagneton. Es wurden Strahlen verschiedener Breite verwendet, bis herab zu etwa 0,03 mm. Da die Strahlen nicht monochromatisiert waren, sondern Maxwellverteilung hatten, und das Aufspaltungsbild ziemlich

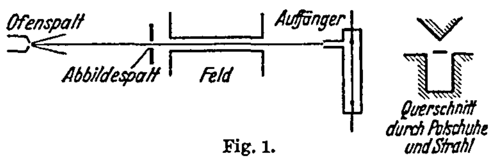

Fig. 1.

kompliziert ist, bekommt man keine wirkliche Aufspaltung in die einzelnen Komponenten, sondern das gesuchte magnetische Moment muß aus der Intensitätsverteilung der abgelenkten Moleküle erschlossen werden.

Infolge der großen Länge und geringen Höhe des Strahles war seine Intensität außerordentlich klein; in einem Auffänger mit idealem Spalt würde der durch den Strahl erzeugte Druck nur etwa $2 \cdot 10^{-8}$ mm betragen, entsprechend einem Galvanometerausschlag von 1,6 cm. Wir mußten daher den üblichen Kunstgriff anwenden, den Spalt kanalförmig zu gestalten, und mußten dabei das Verhältnis Kanallänge zu Kanalbreite besonders groß machen; der Faktor $\varkappa$, um den der Druck durch diese Maßnahme vergrößert wird, betrug in unserem Falle etwa 50, der Ausschlag also etwa 80 cm, was genügende Intensität auch für die abgelenkten Moleküle ergibt. Dieser hohe $\varkappa$-Faktor in Verbindung mit der kleinen Spaltöffnung hat aber zur Folge, daß es sehr lange dauert, bis der Enddruck im Manometer praktisch erreicht wird; diese Zeit hätte bei den üblichen Manometern mit etwa 20 cm³ Volumen etwa $^1/_2$ Stunde betragen. Wir mußten deshalb Manometer mit sehr viel kleinerem Volumen konstruieren. Die von uns angewandten Manometer hatten nur etwa $^1/_2$ cm³ Volumen, wodurch die Einstellzeit auf den 40. Teil, also auf $^3/_4$ Minute heruntergedrückt wurde.

Experimentelle Einzelheiten (siehe Fig. 2 und 3). Der „Ofen“ bestand aus einem Kupferrohr, an dessen vorderem Ende der Ofenspalt saß, aus dem die H_2-Moleküle in das Vakuum eintraten, der also die Strahlenquelle

darstellt Die H_2-Zufuhr erfolgte vom anderen Ende aus durch ein dünnwandiges Neusilberrohr (zur thermischen Isolierung des Ofens), das an

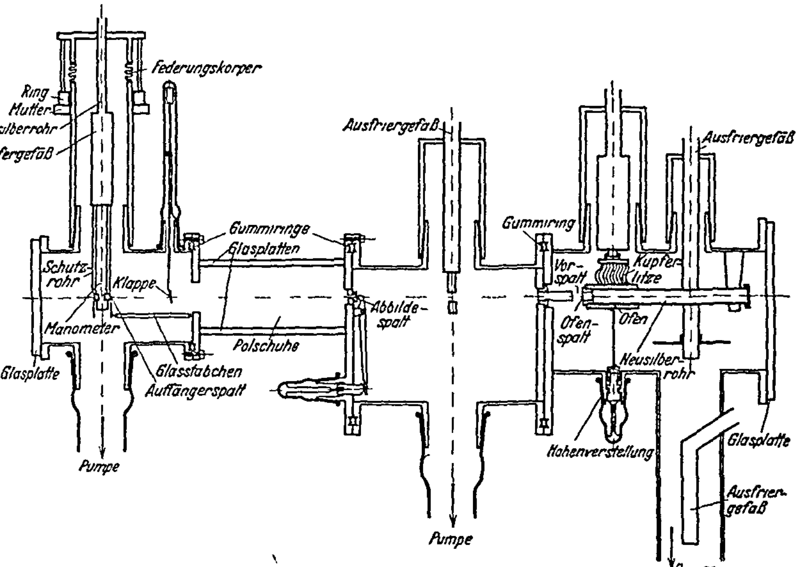

Fig 2 Längsschnitt in der Spaltebene

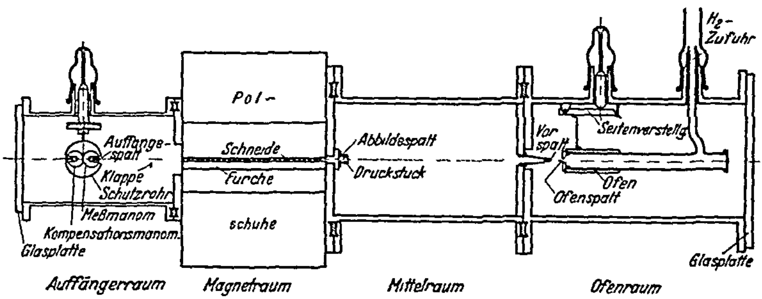

Fig 3 Längsschnitt senkrecht zur Spaltebene

einem Ende am Apparatgehäuse festgeklemmt war. Eine seitliche Abzweigung aus biegsamem Bleirohr diente zur Verbindung mit dem H_2-Vorratsgefäß; auf das rückwärtige Ende des Neusilberrohres war ein Glasfenster aufgekittet, um den Ofenspalt von hinten beleuchten zu können.

Die Elastizität des Neusilberrohres gestattete es, den Ofen mittels zweier Mikrometerschrauben sowohl in der Höhe als auch seitwärts um kleine Beträge zu verschieben. Zur Kühlung des Ofens war an ihm ein Band aus Kupferlitze angelötet (Gesamtquerschnitt $\sim 20\,\mathrm{mm}^2$, Länge etwa 2 cm), an dessen anderem Ende ein mit Woodschem Metall gefüllter Kupfernapf angelötet war; in diesen Napf tauchte ein Kupferzapfen am Boden eines Neusilbergefäßes, das mit flüssiger Luft gefüllt werden konnte. Durch das Einschmelzen mittels Woodschem Metall wurde der erforderliche gute Wärmekontakt erreicht.

Der *Vorspalt* stand etwa 6 mm vor dem Ofenspalt, so daß die Moleküle vom Ofenspalt aus nur diese kurze Strecke in dem relativ hohen Druck

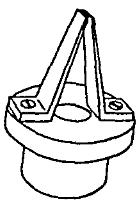

Fig. 4. Vorspalt.

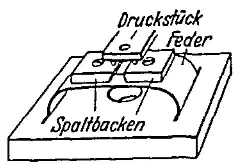

Fig 5. Abbildespalt.

(einige 10^{-4} mm) im Ofenraum laufen mußten; hinter dem Vorspalt, im Mittelraum, wurde durch eine zweite Pumpe wesentlich besseres Vakuum (1 bis $2 \cdot 10^{-5}$ mm) aufrechterhalten. Der Vorspalt war ebenso wie der Ofenspalt nur 0,02 mm breit, so daß eine eventuelle Verbreiterung des Strahles durch Streuung im Ofenraum ohne Einfluß blieb. Man kann gewissermaßen den Vorspalt als die eigentliche Strahlenquelle ansehen; Streuung im Mittelraum spielte bei dem geringen Druck darin keine Rolle mehr. Durch diesen Kunstgriff gelang es Strahlen zu erhalten, deren Intensitätsverteilung („Form") recht genau der Geometrie der Spaltanordnung entsprach und die insbesondere praktisch keine „Schwänze" hatten. Um möglichst wenig durch reflektierte Molekule gestört zu werden, wurde der Vorspalt schnabelförmig ausgebildet (Fig. 4); die Spaltbacken waren dünne geschliffene Stahlstreifen, die federnd gegeneinander drückten und durch kleine Stückchen Platinfolie im richtigen Abstand (0,02 mm) gehalten wurden; seitlich wurden sie mit Aluminiumfolie abgeschlossen (mittels Picein). Der Vorspalt wurde an der richtigen Stelle festgeschraubt (siehe unter Justierung) und konnte während des Versuchs nicht verschoben werden.

Der *Abbildespalt* war so eingerichtet, daß man seine Breite während des Versuchs verändern konnte; das erleichterte einmal das Auffinden

des Strahles, zweitens erwies es sich als sehr vorteilhaft, daß man Aufspaltungsversuche mit verschieden breiten Strahlen ohne großen Zeitverlust vornehmen konnte. Die beiden Spaltbacken waren auf einem federnden Blechstreifen montiert (Fig. 5) und konnten durch Druck mittels eines geeignet geformten Druckstuckes einander bis zur Beruhrung genähert werden; Feder und Druckstuck waren naturlich durchbrochen, um den Strahl durchzulassen. Das Druckstuck saß am kurzeren Ende eines zweiarmigen Hebels, auf dessen längeres Ende eine Mikrometerschraube wirkte. So konnte der Spalt sehr feinfuhlig von 0,2 mm bis zu beliebig geringer Breite verstellt werden.

Der *Auffangespalt* war ebenso wie der Ofenspalt 0,02 mm breit und 0,5 mm hoch. Er war kanalformig ausgebildet mit einer Kanallange von

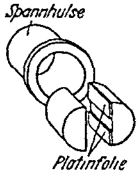

Fig. 6. Auffangespalt, auseinandergenommen.

Fig 7. Meßmanometer.

4 mm; Einzelheiten seiner Konstruktion siehe Fig. 6. Aus diesen Daten berechnet sich der $\varkappa$-Faktor zu[1])

$$\varkappa = \frac{l}{b} \cdot \frac{1}{0{,}5 + 2{,}3 \log \frac{2a}{b}} \doteq \sim 45$$

(b = Spaltbreite, a = Spalthohe, l = Kanallänge). Dieser ungewöhnlich große $\varkappa$-Faktor (bisher wurde er selten größer als 10 gewählt) in Verbindung mit der kleinen Spaltoffnung bedingte, wie schon oben dargelegt, die Konstruktion von Manometern mit besonders kleinem Volumen.

Das *Meßmanometer* bestand aus einem Stuck Messingrohr von 2 mm lichter Weite und etwa 11 cm Länge, in dem axial der Hitzdraht ausgespannt war (Nickelband 3 × 50 μ, 10 cm lang). Seine Zuleitungen aus Platindraht (eine davon als Spiralfeder ausgebildet, um ihn zu spannen) waren durch konische Messingstopfen durchgelötet, die in die konisch erweiterten Enden des Messingrohres eingesetzt waren, isoliert durch dunne Galalithringe. Der Auffangerspalt war in eine seitliche Bohrung eingesetzt. Das ubliche, ganz gleich gebaute Kompensationsmanometer war mit dem

[1]) Berechnet nach M. v. Smoluchowski, Ann. d. Phys. 33, 1559, 1910.

Meßmanometer der Länge nach verlötet, um besten Temperaturausgleich zu erzielen. Die Manometer waren an dem Boden eines kupfernen Kühlgefäßes angeschraubt, das oben einen langen Hals aus Neusilberrohr hatte und für die Messung mit flüssiger Luft gefüllt wurde. Ein kupfernes Schutzrohr, das ebenfalls am Boden des Kühlgefäßes angeschraubt war, schützte die Manometer vor Wärmezustrahlung; ein kleines Loch ließ den Molekularstrahl zum Auffangespalt durchtreten.

Um die Intensitätsverteilung im Strahl ausmessen zu können, mußte der Auffänger quer durch den Strahl durchbewegt werden; doch betrug die ganze erforderliche Verschiebung nur einige Zehntel Millimeter, so daß eine geringe elastische Verbiegung des Neusilberrohres völlig ausreichte. Die Verschiebung erfolgte durch eine Mikrometerschraube, unter Zwischenschaltung eines beiderseits zugespitzten Druckstiftes, zur Vermeidung von Reibung und Wärmezufuhr. Um ein Ausweichen der Manometer in der zur Verschiebung senkrechten Richtung (in Richtung des Strahles) zu verhindern, waren sie in dieser Richtung durch ein beiderseits zugespitztes Glasstäbchen abgestützt.

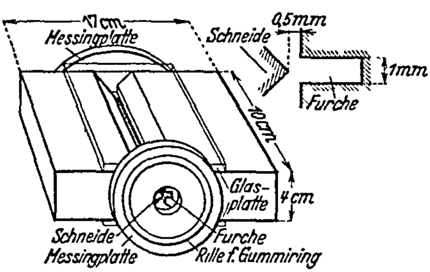

Fig. 8. Magnetfeld.

Um die bei Kühlung erfolgende Längenänderung des Kühlgefäßes und der Manometer selbst (etwa 1 mm) zu kompensieren, konnten die Manometer der Höhe nach verschoben werden; zu diesem Zweck war in dem das Kühlgefäß tragenden äußeren Messingrohr ein Federungskörper aus gewelltem Tombakrohr eingeschaltet; der obere Teil des Rohres war durch vier Stäbe mit einem Ring verbunden, der auf dem unteren Teil verschiebbar war; der Ring saß auf einer großen Mutter auf und konnte durch Drehen derselben in der Höhe verschoben werden.

Das *inhomogene Magnetfeld* wurde von zwei Polschuhen gebildet, deren Form und Dimensionen aus Fig. 8 hervorgehen. Sie waren an den Stirnseiten mit Messingplatten verschraubt, an die wiederum die anschließenden Gehäuseteile angeschraubt wurden; oben und unten waren sie mit Glasplatten abgedeckt, die mit Picein angekittet waren; ebenso waren alle anderen Fugen mit Picein überschmolzen. Mit dieser einfachen Konstruktion wurde eine völlig ausreichende Abdichtung erreicht, mit dem

weiteren Vorteil, daß man durch die Glasplatten die Polschuhe der ganzen Länge nach überblicken konnte.

Die übrigen *Gehäuseteile* (vgl. Fig. 2 und 3), nämlich Ofenraum, Mittelraum und Auffangerraum, waren durch Flansche mit Gummiringdichtung miteinander bzw. mit dem Magnetraum verbunden. Der *Ofenraum* enthielt den oben beschriebenen Ofen mit Kühl- und Verschiebeeinrichtung sowie ein Kühlgefäß zum Ausfrieren von Dämpfen; er wurde durch eine große (dreistufige) Stahlpumpe ausgepumpt (Sauggeschwindigkeit mit Verbindungsrohr 10 Liter/sec für Luft, also etwa 36 Liter/sec für H_2). Der *Mittelraum* war so eingerichtet, daß man für Versuche mit „monochromatischen" Strahlen ein System von rasch rotierenden Zahnscheiben einbauen konnte, das nur Moleküle eines engen Geschwindigkeitsbereiches passieren läßt. Zu diesem Zweck war er ziemlich geräumig (9 cm Durchmesser) und der Strahl lief nahe an der Wand (1 cm Abstand). Bei den vorliegenden Versuchen wurde noch ohne „Monochromator" gearbeitet; statt seiner wurde nur eine Platte eingesetzt, die den Vorspalt trug. Der Vorspalt ragte durch ein Loch in der Zwischenwand in den Ofenraum; der Luftspalt zwischen der Platte, die den Vorspalt trug, und der Zwischenwand wurde mit Ramsayfett abgedichtet, so daß der Vorspalt selbst die einzige Verbindung zwischen Mittelraum und Ofenraum bildete. Auch der Mittelraum enthielt ein Kühlgefäß. Er wurde durch eine zweite Pumpe evakuiert (Sauggeschwindigkeit mit Saugleitung und Kühlfalle etwa 1 Liter/sec für Luft). *Magnetraum* und *Auffangerraum* wurden gemeinsam durch eine dritte Pumpe ähnlicher Sauggeschwindigkeit evakuiert; da sie mit dem Mittelraum nur durch einen kleinen Kanal (etwa 1 mm Durchmesser, 2 mm lang) kommunizierten, konnte in ihnen während des Versuchs Hängevakuum aufrechterhalten werden. Der Abbildespalt saß dicht am Anfang des Magnetfeldes. Im Auffangerraum befand sich außer den schon besprochenen Manometern die elektromagnetisch betätigte Klappe zum Absperren des Strahles, die am Ende eines langen Hebels saß, an dessen anderem Ende, in hinreichendem Abstand vom Magnetfeld, ein Eisenanker befestigt war.

Die *Justierung* geschah teils optisch, teils mit den Molekularstrahlen selbst. Zunächst wurde der Abbildespalt am Magnetfeld befestigt, und zwar so, daß seine Mittellinie zwischen der Furchenebene und der Schneide lag, dicht (etwa 0,1 mm) über der Furchenebene; das war mittels eines Mikroskops leicht zu kontrollieren. Dann wurde der Mittelraum mit dem Vorspalt montiert; ein Lichtstrahl (Wolframpunktlampe) wurde durch Vorspalt und Abbildespalt geschickt und der Vorspalt so lange verschoben,

bis der Lichtstrahl das Feld genau parallel zu den Polschuhkanten durchlief. Nun wurde die Punktlampe an ihrem Ort belassen, der Ofenraum montiert und der Ofen so lange verschoben, bis der Strahl seine größte Helligkeit hatte. Damit waren diese drei Spalte in eine Linie gestellt und richtig zum Feld justiert. Ihre gegenseitige Parallellage wurde dadurch gesichert, daß jeder einzeln ins Lot gestellt wurde; darauf kam es nicht so sehr genau an, da der Strahl ja nur $^1/_2$ mm hoch, das Verhältnis Länge zu Breite also nur etwa 25 war; ein Fehler von 1^0 in der Vertikalstellung, der sicher nicht vorkam, hätte noch nicht viel geschadet.

Die Justierung des Auffängers und die Feinjustierung des Ofens erfolgte mit dem Molekularstrahl selbst. Insbesondere mußte der Auffangespalt so gestellt werden, daß die Molekule wirklich durch den Kanal durchlaufen konnten, ohne die Wand zu treffen; da die Kanallänge das 200fache der Kanalbreite war, setzte schon eine Verdrehung um $^1/_{200} = 0{,}3^0$ den Druck im Auffänger auf die Hälfte herab; man mußte also auf wenige Bogenminuten genau zielen; zu diesem Zweck war ein langer kräftiger Arm mit Mikrometerverschiebung am Auffängerschliff befestigt.

Ergebnisse. Es wurden zuerst Strahlen aus gewöhnlichem H_2 bei tiefer Temperatur (flussiger Luft) untersucht. Zur Deutung dieser Versuche ist folgendes zu sagen: Gewohnlicher Wasserstoff besteht aus 25% Parawasserstoff und 75% Orthowasserstoff. Beim Para-H_2 stehen die beiden Protonen antiparallel, er sollte also kein vom Kernspin herruhrendes magnetisches Moment haben. Dagegen ist zu erwarten, daß die Rotation der Molekule ein magnetisches Moment erzeugt. Bei der Temperatur der flüssigen Luft haben aber die Para-H_2-Molekule fast alle (99%) die Rotationsquantenzahl 0; der Para-H_2 sollte also bei dieser Temperatur kein magnetisches Moment haben. Wir haben das durch Versuche an reinem Para-H_2 bestätigt.

Beim Ortho-H_2 stehen die beiden Protonen parallel, er hat also aus diesem Grunde ein magnetisches Moment vom Betrag 2 Protonenmomente. Außerdem gibt wiederum die Rotation einen Beitrag zum magnetischen Moment; und in diesem Falle ist dieser Beitrag nicht durch Erniedrigung der Temperatur wegzuschaffen, da der niedrigste Rotationszustand vom Ortho-H_2 die Quantenzahl 1 hat. Da die Kopplung zwischen den beiden Momenten (Rotation und Kernspin) sehr klein und in den zur Aufspaltung benutzten Feldern von etwa 20000 Gauß sicher völlig aufgehoben ist, ist für einen Ortho-H_2-Strahl einheitlicher Geschwindigkeit bei tiefer Temperatur das Aufspaltungsbild Fig. 9 zu erwarten. Jedes der beiden

Momente hat drei Einstellungen im Feld (entsprechend der Quantenzahl 1); in der Figur ist angenommen, daß das Rotationsmoment viel kleiner ist als das Kernmoment. Bei den wirklich verwendeten Strahlen mit Maxwell-Ferteilung der Geschwindigkeiten entspricht jedem Strich der obigen vigur (außer dem Mittelstrich) eine Maxwellkurve; die gemessene Intensitätsverteilung ist die Überlagerung dieser Kurven. Unter S_R bzw. S_P ist im Folgenden immer die Ablenkung für Moleküle der wahrscheinlichsten Geschwindigkeit verstanden.

Prinzipiell könnte man aus der gemessenen Intensitätsverteilung die beiden Unbekannten S_R und S_P (s. Fig. 9) errechnen; doch würde das eine sehr hohe Genauigkeit der Messungen voraussetzen. Wir haben daher die eine Unbekannte, das Rotationsmoment, d. h. S_R, auf folgendem Wege bestimmt. Wir haben reinen Para-H_2[1]) außer bei der Temperatur der flüssigen Luft auch bei höheren Temperaturen (festes CO_2, d. h. 195° abs. und Zimmertemperatur, d. h. 292° abs.) untersucht. Bei der Temperatur der flüssigen Luft war er, wie erwähnt, unmagnetisch[2]); bei höheren Temperaturen zeigte er ein Moment, das von den dann auftretenden höheren Rotationsquantenzuständen herrührt. Wir haben die Häufigkeit dieser Quantenzustände nach der Boltzmannformel berechnet; bezeichnet man die Rotationsquantenzahl mit n, so ergibt für $T = 195°$ abs. die Rechnung 73% Moleküle mit $n = 0$, und 27% mit $n = 2$; bei Zimmertemperatur (292° abs.) findet man 52,5% mit $n = 0$, 46,1% mit $n = 2$, und 1,4% mit $n = 4$. Unter der Voraussetzung, daß die auftretenden Komponenten des magnetischen Moments (vgl. Fig. 10) alle ganzzahlige Vielfache eines Grundmoments sind, das $n = 1$ entspricht, können wir dieses Grundmoment μ_R aus den Messungen entnehmen; es ergibt sich zu etwa ein Kernmagneton, eher etwas kleiner.

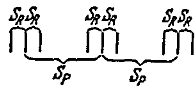

Fig. 9. Aufspaltungsbild von Orthowasserstoff

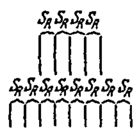

Fig. 10. Aufspaltungsbild für Parawasserstoff; oben $n = 2$, unten $n = 4$

Auf die Art der Ausrechnung des Moments soll noch etwas näher eingegangen werden. Es wurde zunächst die Form des unaufgespaltenen Strahles ausgemessen. Unter Form des Strahles verstehen wir immer die Form der Kurve, die man erhält, wenn man den Auffänger quer durch den

[1]) Hergestellt von Herrn I. Estermann, wofur wir ihm besten Dank schuldig sind.

[2]) Ein kleiner Betrag von magnetischen Molekülen kam offenbar von einer geringen Verunreinigung (3 bis 4%) mit Ortho-H_2.

Strahl durchbewegt und die gemessene Intensität als Funktion der Auffängerverschiebung aufträgt; Beispiel siehe Fig. 11. Die Form des Strahles stimmte recht gut mit der geometrisch zu erwartenden Form überein, falls das remanente Feld des Magneten durch einen schwachen Gegenstrom (0,2 Amp.) beseitigt wurde. Sodann wurde das Feld eingeschaltet und die Strahlform neuerdings ausgemessen (Fig. 11 und 12). Wie daraus das

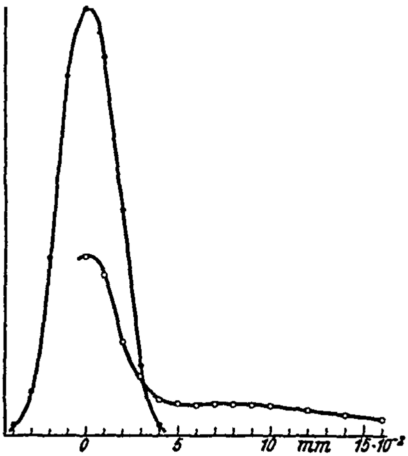

Fig. 11. Beispiel einer Messung an gewöhnlichem Wasserstoff bei 95° abs.; Stahlform ohne Feld (●) und mit Feld (○).

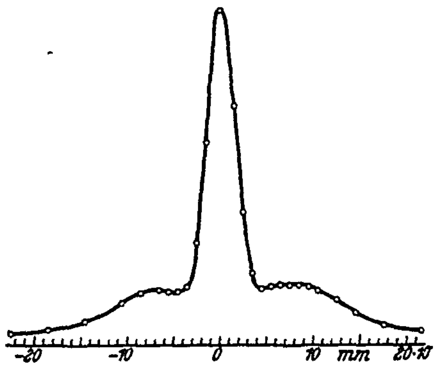

Fig. 12. Vollständiges Aufspaltungsbild von gewöhnlichem Wasserstoff bei 95° abs.; die Unsymmetrie ist apparativ bedingt.

Moment berechnet wurde, sei an dem Beispiel „Para-H_2 bei 195° abs.“ besprochen.

Wir greifen irgendeinen Punkt der gemessenen Kurve heraus, dessen Abstand von der Mitte hinreichend groß gegen die Strahlbreite ist (praktisch genügt ein Abstand gleich der Strahlbreite). Wir wissen nun, daß 73% der Moleküle die Rotationsquantenzahl $n = 0$ haben, also unmagnetisch sind und überhaupt nichts zur Intensität an dieser Stelle beitragen. Von den restlichen 27% wird ein Fünftel ebenfalls nicht abgelenkt (s. Fig. 10, oben), während zwei Fünftel in zwei Strahlen aufgespalten werden, genau wie ein Strahl von Silberatomen, nur mit dem sehr viel kleineren Moment μ_R, wie es durch die Rotation eines H_2-Moleküls mit einem Rotationsquant erzeugt wird, und die restlichen zwei Fünftel genau so, nur mit dem doppelten Moment.

Wir können nun dem Rotationsmoment versuchsweise irgendeinen Wert erteilen, z. B. ein Kernmagneton; daraus können wir s_α, die Ablenkung für Moleküle mit der wahrscheinlichsten Geschwindigkeit, berechnen

und daraus unter Berücksichtigung der Maxwellverteilung die Intensität in dem betreffenden Abstand von der Strahlmitte[1]). Für diese Berechnung haben wir angenommen, daß der ursprüngliche Strahl Rechtecksform besitzt mit einer Breite, die gleich der Halbwertsbreite des gemessenen Strahls ist; diese Vereinfachung ist in unserem Falle völlig unbedenklich, wie wir durch Kontrollrechnung sichergestellt haben. Es wurde nun μ_R so lange variiert, bis die berechneten Intensitäten mit den gemessenen übereinstimmten.

Ein zweiter Weg, auf dem wir diese Werte verifizierten, war der, die Intensität in der Mitte des Strahles mit und ohne Feld zu messen. Auch hier benutzten wir bei der Berechnung wieder die Vereinfachung, den unabgelenkten Strahl als rechteckig zu behandeln, was hier ebenfalls unbedenklich war, da wir diese Methode vor allem bei sehr breiten Strahlen verwendeten, die wirklich mit großer Annäherung Rechtecksform aufwiesen.

In prinzipiell der gleichen Weise wurden die Messungen an gewöhnlichem Wasserstoff ausgewertet. Wir nehmen an, daß μ_R auch das magnetische Rotationsmoment des einquantigen Ortho-H_2 ist. Rechnen wir mit diesem Wert des Rotationsmoments aus unseren Messungen an gewöhnlichem H_2 das von den Protonen herrührende Moment aus, so ergibt es sich zu etwa 5 Kernmagnetonen pro Ortho-H_2-Molekül. Das magnetische Moment eines Protons wäre also danach nicht ein Kernmagneton, sondern etwa 2 bis 3 Kernmagnetonen. Dieser Zahlenwert ist nicht sehr genau; doch scheint ein Wert von der Größe 1 mit den Messungen nicht vereinbar zu sein.

Zum Rotationsmoment sei noch folgendes gesagt: Wir machten anfangs nur Messungen mit gewöhnlichem H_2 und versuchten, für das Rotationsmoment einen theoretisch berechneten Wert zu verwenden. Auf Veranlassung von Herrn Fermi hatte Herr Bethe die Freundlichkeit, das elektrische Trägheitsmoment des H_2-Moleküls abzuschätzen. Aus seinen Rechnungen ergab sich unter der Annahme, daß das H_2-Molekül wie ein starrer Körper rotiert, für das Rotationsmoment ein Wert von etwa 3 Kernmagnetonen (für die Rotationsquantenzahl eins). Erst später kamen wir darauf, daß man in der oben beschriebenen Weise durch Messungen an reinem Parawasserstoff das Rotationsmoment direkt experimentell bestimmen kann. Es ergab sich, wie erwähnt, ein Wert von höchstens einem Kernmagneton. Da diese Diskrepanz weit außerhalb der Fehlergrenzen

[1]) Siehe z. B. U. z. M. Nr. 5; O. Stern, ZS. f. Phys. 41, 563, 1927.

sowohl der theoretischen Abschätzung als auch unserer Messungen lag, wandten wir uns neuerdings an Herrn Fermi, der dann folgendes herausbrachte: Die Annahme, daß das Wasserstoffmolekül wie ein starrer Körper rotiert, ist unzutreffend; man muß sich vielmehr vorstellen, daß die Elektronenhülle bei der Rotation zurückbleibt („rutscht"). Eine Abschätzung dieses Effektes, die Herr Wick[1]) auf Anregung von Herrn Fermi vornahm, ergab, daß das Rotationsmoment zwischen 0,85 und 0,92 Kernmagnetonen liegen sollte. Das ist mit unseren Messungen vereinbar; wir möchten vermuten, daß der wirkliche Wert näher an der oberen Grenze liegt.

[1]) ZS. f. Phys. 85, 25, 1933.

Zur Quantentheorie des Atomkernes.

Von G. Gamow, z. Zt. in Göttingen.

Mit 5 Abbildungen. (Eingegangen am 2. August 1928.)

Es wird der Versuch gemacht, die Prozesse der α-Ausstrahlung auf Grund der Wellenmechanik näher zu untersuchen und den experimentell festgestellten Zusammenhang zwischen Zerfallskonstante und Energie der α-Partikel theoretisch zu erhalten.

§ 1. Es ist schon öfters* die Vermutung ausgesprochen worden, daß im Atomkern die nichtcoulombschen Anziehungskräfte eine sehr wichtige Rolle spielen. Über die Natur dieser Kräfte können wir viele Hypothesen machen.

Es können die Anziehungen zwischen den magnetischen Momenten der einzelnen Kernbauelemente oder die von elektrischer und magnetischer Polarisation herrührenden Kräfte sein.

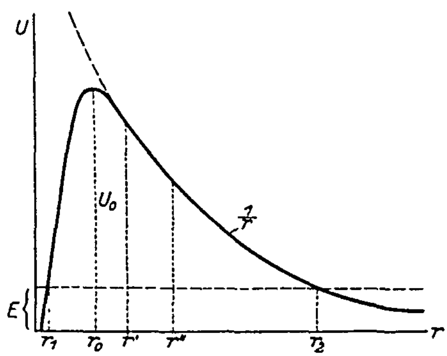

Fig. 1.

Jedenfalls nehmen diese Kräfte mit wachsender Entfernung vom Kern sehr schnell ab, und nur in unmittelbarer Nähe des Kernes überwiegen sie den Einfluß der Coulombschen Kraft.

Aus Experimenten über Zerstreuung der α-Strahlen können wir schließen, daß, für schwere Elemente, die Anziehungskräfte bis zu einer Entfernung $\sim 10^{-12}$ cm noch nicht merklich sind. So können wir das auf Fig. 1 gezeichnete Bild für den Verlauf der potentiellen Energie annehmen.

Hier bedeutet r'' die Entfernung, bis zu welcher experimentell nachgewiesen ist, daß Coulombsche Anziehung allein existiert. Von r' beginnen die Abweichungen (r' ist unbekannt und vielleicht viel kleiner als r'') und bei r_0 hat die U-Kurve ein Maximum. Für $r < r_0$ herrschen schon die Anziehungskräfte vor, in diesem Gebiet würde das Teilchen den Kernrest wie ein Satellit umkreisen.

* J. Frenkel, ZS. f. Phys. 37, 243, 1926; E. Rutherford, Phil. Mag. 4, 580, 1927; D. Enskog, ZS. f. Phys. 45, 852, 1927.

Diese Bewegung ist aber nicht stabil, da seine Energie positiv ist, und nach einiger Zeit wird das α-Teilchen wegfliegen (α-Ausstrahlung). Hier aber begegnen wir einer prinzipiellen Schwierigkeit.

Um wegzufliegen, muß das α-Teilchen eine Potentialschwelle von der Höhe U_0 (Fig. 1) überwinden, seine Energie darf nicht kleiner als U_0 sein. Aber die Energie der α-Partikel ist, wie experimentell nachgewiesen ist, viel kleiner. Z. B. findet man * bei der Untersuchung der Streuung von RaC'-α-Strahlen, als sehr schnelle Partikel, an Uran, daß für den Urankern das Coulombsche Gesetz bis zu einer Entfernung von $3{,}2 \cdot 10^{-12}$ cm gilt. Andererseits haben die von Uran selbst emittierten α-Partikeln eine Energie, die auf der Abstoßungskurve einem Kernabstand von $6{,}3 \cdot 10^{-12}$ cm (r_2 in Fig. 1) entspricht. Soll eine α-Partikel, die aus dem Inneren des Kernes kommt, wegfliegen, so müßte sie das Gebiet zwischen r_1 und r_2 durchlaufen, wo ihre kinetische Energie negativ wäre, was nach klassischen Vorstellungen natürlich unmöglich ist.

Um diese Schwierigkeit zu überwinden, machte Rutherford ** die Annahme, daß die α-Partikel im Kerne neutral ist, da sie dort noch zwei Elektronen enthalten soll. Erst bei einem gewissen Kernabstand jenseits des Potentialmaximums verliert sie, nach Rutherford, ihre beiden Elektronen, die in den Kern zurückfallen, und fliegt weiter unter Entwirkung der Coulombschen Abstoßungskraft. Aber diese Annahme scheint sehr unnatürlich und dürfte kaum den Tatsachen entsprechen.

§ 2. Betrachten wir die Frage vom Standpunkt der Wellenmechanik, so fällt die oben erwähnte Schwierigkeit von selbst fort. In der Wellenmechanik nämlich gibt es für ein Teilchen immer eine von Null verschiedene Übergangswahrscheinlichkeit, von einem Gebiet in ein anderes Gebiet gleicher Energie, das durch eine beliebig, aber endlich hohe Potentialschwelle von dem ersten getrennt ist ***.

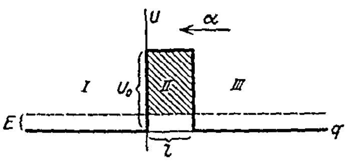

Fig. 2.

Wie wir weiter sehen werden, ist die Wahrscheinlichkeit eines solchen Überganges allerdings sehr klein, und zwar um so kleiner, je

* Rutherford, l. c., S. 581.

** Derselbe, l. c., S. 584.

*** Siehe z. B. Oppenheimer, Phys. Rev. 31, 66, 1928; Nordheim, ZS. f. Phys. 46, 833, 1927.

höher die zu überwindende Potentialschwelle ist. Um diese Tatsache zu erläutern, wollen wir ein einfaches Beispiel untersuchen.

Wir haben eine rechteckige Potentialschwelle und wir wollen die Lösung der Schrödingerschen Gleichung finden, welche den Durchgang der Partikel von rechts nach links darstellt. Für die Energie E schreiben wir die Wellenfunktion ψ in der folgenden Form:

$$\psi = \Psi(q) \cdot e^{+\frac{2\pi i E}{h} t},$$

wo $\Psi(q)$ der Amplitudengleichung:

$$\frac{\partial^2 \psi}{\partial q^2} + \frac{8\pi^2 m}{h^2}(E - U)\Psi = 0 \tag{1}$$

genügt.

Für das Gebiet I haben wir die Lösung

$$\Psi_{\mathrm{I}} = A \cos(kq + \alpha),$$

wo A und α zwei beliebige Konstanten sind und

$$k = \frac{2\pi\sqrt{2m}}{h} \cdot \sqrt{E} \tag{2a}$$

bedeutet. In dem Gebiet II lautet die Lösung

$$\Psi_{\mathrm{II}} = B_1 e^{-k'q} + B_2 e^{+k'q},$$

wo

$$k' = \frac{2\pi\sqrt{2m}}{h}\sqrt{U_0 - E} \tag{2b}$$

ist.

An der Grenze $q = 0$ gelten die Bedingungen:

$$\psi_{\mathrm{I}}(0) = \psi_{\mathrm{II}}(0) \quad \text{und} \quad \left[\frac{\partial \Psi_{\mathrm{I}}}{\partial q}\right]_{q=0} = \left[\frac{\partial \Psi_{\mathrm{II}}}{\partial q}\right]_{q=0},$$

woraus wir leicht

$$B_1 = \frac{A}{2\sin\vartheta}\sin(\alpha + \vartheta); \quad B_2 = -\frac{A}{2\sin\vartheta}\sin(\alpha - \vartheta)$$

erhalten, wo

$$\sin\vartheta = \frac{1}{\sqrt{1 + \left(\frac{k}{k'}\right)^2}}$$

ist.

Die Lösung im Gebiet II lautet daher:

$$\Psi_{\mathrm{II}} = \frac{A}{2\sin\vartheta}[\sin(\alpha + \vartheta) \cdot e^{-k'q} - \sin(\alpha - \vartheta)\, e^{+k'q}].$$

In III haben wir wieder:

$$\Psi_{\mathrm{III}} = C\cos(kq + \beta).$$

An der Grenze $q = l$ haben wir aus den Grenzbedingungen:

$$\frac{A}{2\sin\vartheta}\left[\sin(\alpha+\vartheta)\, e^{-lk'} - \sin(\alpha-\vartheta)\, e^{+lk'}\right] = C\cos(kl+\beta)$$

und

$$\frac{A}{2\sin\vartheta}\, k'\left[-\sin(\alpha+\vartheta)\, e^{-lk'} - \sin(\alpha-\vartheta)\, e^{+lk'}\right] = -kC\cos(kl+\beta)$$

So ist

$$\begin{aligned} C^2 = \frac{A^2}{4\sin^2\vartheta}\Bigg\{&\left[1+\left(\frac{k'}{k}\right)^2\right]\sin^2(\alpha-\vartheta)\,.\,e^{2lk} \\ &-\left[1-\left(\frac{k'}{k}\right)^2\right]2\sin(\alpha-\vartheta)\sin(\alpha+\vartheta) \\ &+\left[1+\left(\frac{k'}{k}\right)^2\right]\sin^2(\alpha+\vartheta)\, e^{-2lk'}\Bigg\}. \end{aligned} \tag{3}$$

Die Ausrechnung des β ist fur uns nicht von Interesse. Uns interessiert nur der Fall, wo lk' sehr groß ist, so daß wir nur das erste Glied in (3) zu berucksichtigen brauchen

So haben wir die folgende Lösung

Links. Rechts

$$A\cos(kq+\alpha)\ \ldots\ A\frac{\sin(\alpha-\vartheta)}{2\sin\vartheta}\left[1+\left(\frac{k'}{k}\right)^2\right]^{\frac{1}{2}}.\, e^{+lk'}\cos(kq+\beta)$$

Wenn wir jetzt $\alpha - \frac{\pi}{2}$ statt α schreiben, die erhaltene Lösung mit i multiplizieren und beide Lösungen addieren, so erhalten wir links

$$\Psi = A e^{i(kq+\alpha)}, \tag{4a}$$

rechts aber:

$$\begin{aligned} \Psi = \frac{A}{2\sin\vartheta}\left[1+\left(\frac{k'}{k}\right)^2\right]^{\frac{1}{2}}.\, e^{+lk'}\{&\sin(\alpha-\vartheta)\cos(kq+\beta) \\ &- i\cos(\alpha+\vartheta)\cos(kq+\beta')\}, \end{aligned} \tag{4b}$$

wo β' die neue Phase ist

Multiplizieren wir diese Lösung mit $e^{2\pi i\frac{E}{h}t}$, so erhalten wir fur ψ links die (von rechts nach links) laufende Welle, rechts aber den komplizierten, von der stehenden Welle wenig abweichenden Schwingungsprozeß mit einer sehr großen ($e^{lk'}$) Amplitude Das bedeutet nichts anderes, als daß die von rechts kommende Welle teils reflektiert und teils durchgegangen ist

So sehen wir, daß die Amplitude der durchgegangenen Welle um so kleiner ist, je kleiner die Gesamtenergie E ist, und zwar spielt der Faktor:

$$e^{-lk'} = e^{-\frac{2\pi.\sqrt{2m}}{h}\sqrt{U_0 - E}\,.\,l}$$

in dieser Abhängigkeit die wichtigste Rolle.

§ 3. Jetzt können wir das Problem für zwei symmetrische Potentialschwellen (Fig. 3) lösen. Wir werden zwei Lösungen suchen.

Eine Lösung soll für positive q gelten und für $q > q_0 + l$ die Welle:

$$A\,e^{i\left(\frac{2\pi E}{h}t - kq + \alpha\right)}$$

geben. Die andere Lösung gilt für negative q und gibt für $q < -(q_0 + l)$ die Welle

$$A\,.\,e^{i\left(\frac{2\pi}{h}Et + q\varkappa' - \alpha\right)}.$$

Dann können wir die beiden Lösungen an der Grenze $q = 0$ nicht stetig aneinanderfügen, denn wir haben hier zwei Grenzbedingungen zu

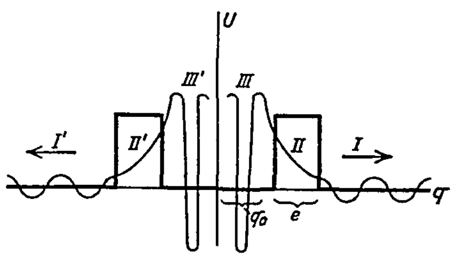

Fig. 3.

erfüllen und nur eine Konstante α zur Verfügung. Die physikalische Ursache dieser Unmöglichkeit ist, daß die aus diesen zwei Lösungen konstruierte ψ-Funktion dem Erhaltungssatz

$$\frac{\partial}{\partial t}\int\limits_{-(q_0+l)}^{+(q_0+l)} \psi\overline{\psi}\,dq = 2\,.\,\frac{-h}{4\pi i m}\left[\psi\,\mathrm{grad}\,\overline{\psi} - \overline{\psi}\,\mathrm{grad}\,\psi\right]_{\mathrm{I}}$$

nicht genügt.

Um diese Schwierigkeit zu überwinden, müssen wir annehmen, daß die Schwingungen gedämpft sind, und E komplex setzen:

$$E = E_0 + i\,\frac{h\lambda}{4\pi},$$

wo E_0 die gewöhnliche Energie ist und λ das Dämpfungsdekrement (Zerfallskonstante). Dann sehen wir aber aus den Relationen (2a) und (2b),

daß auch k und k' komplex sein sollen, d. h., daß die Amplitude unserer Wellen auch von der Koordinate q expotentiell abhängt. Z. B. für die laufende Welle wird die Amplitude in Richtung der Wellenausbreitung wachsen. Das bedeutet aber nichts weiter als daß, wenn die Schwingung am Ausgangspunkt der Welle gedämpft ist, die Amplitude des früher ausgegangenen Wellenstückes größer sein muß. Wir können jetzt α so wählen, daß die Grenzbedingungen erfüllt werden. Aber die strenge Lösung interessiert uns nicht. Wenn λ im Vergleich mit $\frac{E}{h}$ klein ist $\left(\text{für Ra C' ist } \frac{E}{h} \cong \frac{10^{-6}}{10^{-27}\,\text{sec}} = 10^{+22}\,\text{sec}^{-1} \text{ und } \lambda = 10^{+5}\,\text{sec}^{-1}\right)$, so ist die Änderung der $\Psi(q)$ sehr klein, und wir können einfach die alte Lösung mit $e^{-\frac{\alpha}{2}t}$ multiplizieren.

Dann lautet der Erhaltungssatz:

$$\frac{\partial}{\partial t} e^{-\lambda t} \int\limits_{-(q_0+l)}^{+(q_0+l)} \Psi^{(q)}_{\mathrm{II},\mathrm{III}} \cdot \Psi^{(q)}_{\mathrm{II},\mathrm{III}}\, d\,q = -2 \cdot \frac{A^2 h}{4\pi i m} \cdot 2ik \cdot e^{-\lambda t},$$

woraus

$$\lambda = \frac{4hk \sin^2\vartheta}{\pi m\left[1+\left(\frac{k'}{k^0}\right)^2\right] 2(l+q_0)\varkappa} \cdot e^{-\frac{4\pi l\sqrt{2m}}{h}\sqrt{U_0-E}}, \tag{5}$$

folgt, wo $\varkappa$ eine Zahl von der Größenordnung 1 ist.

Diese Formel gibt die Abhängigkeit der Zerfallkonstante von der Zerfallsenergie für unser einfaches Kernmodell.

§ 4. Jetzt können wir zu dem Falle des wirklichen Kernes übergehen.

Wir können die entsprechende Wellengleichung nicht lösen, da wir den genauen Potentialverlauf in der Nähe des Kernes nicht kennen. Aber einige, für unser einfaches Modell erhaltene, Ergebnisse können wir auch auf den wirklichen Kern ohne genaue Kenntnis des Potentialverlaufs übertragen.

Wie gewöhnlich im Falle der Zentralkraft, werden wir die Lösung in Polarkoordinaten suchen, und zwar in der Form

$$\Psi = u(\theta, \varphi)\,\chi(r).$$

Für u erhalten wir die Kugelfunktionen, und χ muß der Differentialgleichung:

$$\frac{\partial^2\chi}{\partial r^2} + \frac{2}{r}\frac{d\chi}{dr} + \frac{8\pi^2 m}{h^2}\left[E - U - \frac{h^2}{8\pi^2 m} \cdot \frac{n(n+1)}{r^2}\right]\chi = 0$$

genügen, wo n die Ordnung der Kugelfunktion ist. Wir können $n = 0$ annehmen, denn wenn $n > 0$, würde das wirklich sein, als ob die potentielle Energie vergrößert wäre, und infolgedessen wird für diese Schwingungen die Dämpfung viel kleiner. Die Partikel muß zuerst in den Zustand $n = 0$ übergehen und kann erst dann wegfliegen.

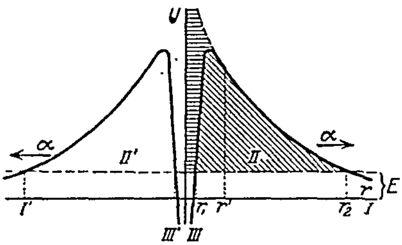

Fig. 4.

Es ist sehr gut möglich, daß derartige Übergänge die γ-Strahlen verursachen, welche stets α-Emission begleiten. Der wahrscheinliche Verlauf von U ist in Fig. 4 wiedergegeben.

Für große Werte von r werden wir für χ die Lösung

$$\chi_{\mathrm{I}} = \frac{A}{r} e^{i\left(\frac{2\pi E}{h} t - k r\right)}$$

annehmen.

Obgleich man die genaue Lösung des Problems in diesem Falle nicht erhalten kann, können wir doch sagen, daß in den Gebieten I und III χ im Mittel nicht rasch $\left(\text{in dreidimensionalem Falle etwa wie } \frac{1}{r}\right)$ abnehmen wird.

Im Gebiet III wird aber χ expotentiell abnehmen, und zwar können wir in Analogie mit unserem einfachen Falle erwarten, daß der Zusammenhang zwischen Amplitudenabnahme und E durch den Faktor:

$$e^{-\frac{2\pi\sqrt{2m}}{h}\int\limits_{r_1}^{r_2}\sqrt{U-E}\,dr}$$

angenähert gegeben ist.

Bei Anwendung des Erhaltungssatzes können wir wieder die Formel:

$$\lambda = D \,.\, e^{-\frac{2\pi\sqrt{2m}}{h}\int\limits_{r_1}^{r_2}\sqrt{U-E}\,dr} \tag{6}$$

schreiben, wo D von den besonderen Eigenschaften des Kernmodells abhängt. Die Abhängigkeit des D von E können wir neben den der expotentiellen Abhängigkeit des zweiten Faktors vernachlässigen.

Wir können auch statt des Integrals

$$\int\limits_{r_1}^{r_2}\sqrt{U-E}\,dr$$

angenähert das Integral:

$$\int_0^{\frac{2Ze^2}{E}} \sqrt{\frac{2Ze^2}{r} - E} \, . \, dr$$

setzen.

Der relative Fehler, den wir dabei begehen, wird von Großenordnung

$$\frac{\int_0^{r_1} \sqrt{\frac{1}{r}}\, dr}{\int_0^{r_2} \sqrt{\frac{1}{r}}\, dr} = \sqrt{\frac{r'}{r_2}}.$$

Da $\frac{r'}{r_2}$ klein ist, so wird dieser Fehler nicht sehr groß. Da bei den verschiedenen radioaktiven Elementen E nicht sehr verschiedene Werte hat, schreiben wir angenähert:

$$\lg \lambda = \lg D - \frac{4\pi\sqrt{2m}}{h}\left\{\int_0^{\frac{2Ze^2}{E_0}} \sqrt{\frac{2Ze^2}{r} - E_0}\, dr + \frac{\partial}{\partial E}\int_0^{\frac{2Ze^2}{E}} \sqrt{\frac{2Ze^2}{r} - E}\, dr \, . \, \varDelta E\right\}$$

oder

$$\lg \lambda = \mathrm{Const}_E + B_E \;\varDelta E,$$

wo

$$B = -\frac{4\pi\sqrt{2m}}{h}\frac{\partial}{\partial E}\int_0^{\frac{2Ze^2}{E}} \sqrt{\frac{2Ze^2}{r} - E}\, dr = \frac{4\pi\sqrt{2m}}{2h}\int_0^{\frac{2Ze^2}{E}} \frac{dr}{\sqrt{\frac{2Ze^2}{r} - E}\, dr}.$$

Setzen wir:

$$\varrho = \frac{E}{2Ze^2}\, r,$$

so ist:

$$b = \frac{4\pi\sqrt{2m}\;2Ze^2}{2hE^{3/2}}\int_0^1 \frac{d\varrho}{\sqrt{\frac{1}{\varrho} - 1}} = \frac{\pi^2\sqrt{2m}\, . \, 2Ze^2}{hE^{3/2}}. \qquad (7)$$

Nun wollen wir diese Formel mit den experimentellen Tatsachen vergleichen. Es ist bekannt*, daß, wenn wir als Abszisse die Energie

* Geiger und Nuttall, Phil. Mag. **23**, 439, 1912, Swinne, Phys. ZS. **13**, 14, 1912.

der α-Partikel, als Ordinate den Logarithmus der Zerfallkonstante auftragen, alle Punkte für eine bestimmte radioaktive Familie auf einer Geraden liegen. Für verschiedene Familien erhält man verschiedene parallele Gerade. Die empirische Formel lautet:

$$\lg \lambda = \text{Const} + b E,$$

wo b eine allen radioaktiven Familien gemeinsame Konstante ist.

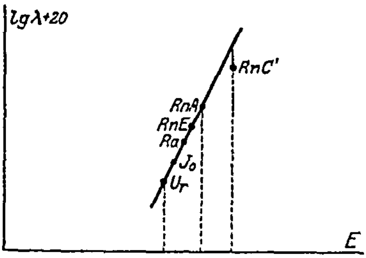

Fig 5

Der experimentelle Wert von b (aus **Ra A** und **Ra** berechnet) ist

$$b_{\text{exper.}} = 1{,}02 \,.\, 10^{+7}.$$

Wenn wir aber in unsere Formel den Energiewert für Ra A einsetzen, so gibt die Rechnung

$$b_{\text{theor}} = 0{,}7 \,.\, 10^{+7}\,*.$$

Die Übereinstimmung der Größenordnung zeigt, daß die Grundannahme der Theorie richtig sein dürfte. Nach unserer Theorie müssen gewisse Abweichungen von dem linearen Gesetz bestehen: mit wachsender Energie muß b abnehmen, d. h., daß $\log \lambda$ etwas langsamer als E abnehmen muß. Hiermit stimmten die Messungen von Jacobsen**, welcher für Ra C', dessen α-Strahlung sehr energiereich ist, als Zerfallskonstante den Wert $8{,}4 \,.\, 10^5$ erhält, während aus dem linearen Gesetz der Wert $5 \,.\, 10^7$ folgt.

Zum Schluß möchte ich noch meinem Freund N. Kotschin meinen besten Dank aussprechen für die freundliche Besprechung der mathematischen Fragen. Auch Herrn Prof. Born möchte ich für die Erlaubnis, in seinem Institut zu arbeiten, herzlich danken.

Göttingen, Institut für theoretische Physik, 29. Juli 1928.

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* Für andere Elemente erhalten wir angenähert denselben Wert, da Z für verschiedene radioaktive Elemente nur wenig verschieden ist.

** Jacobsen, Phil. Mag. **47**, 23, 1924.

synthetischem Asbest[1], von künstlichem Glimmer[2], von künstlichem Kaolin[3] und Montmorillonit[4]. Bei allen diesen Versuchen hat man zwar bisher nur sehr kleine Kristalle erhalten, deren Identifizierung nur mittels Röntgenanalyse sichergestellt werden konnte. Es ist jedoch kein Zweifel, daß hier fruchtbare Ansätze vorliegen, die verfolgt werden müssen.

Interessant ist auch die Tatsache, daß es der Technik gelungen ist, Gewebe aus Glas herzustellen, bei denen die einzelnen Glasfäden die bekannte Sprödigkeit des Glases vollkommen verloren haben, sowie ferner, daß die Beachtung des Isosterismus von Quarz und $AlPO_4$ zu technisch brauchbaren neuartigen Gläsern geführt hat.

Ich möchte schließen mit der Forderung, daß wir uns bei der Suche nach praktisch brauchbaren Stoffen für bestimmte Verwendungszwecke mehr als bisher loslösen müssen von unseren Kenntnissen über die chemische Zusammensetzung des bisher auf dem entsprechenden Anwendungsgebiet Bekannten und daß wir viel mehr als bisher unsere Kenntnisse über Kristallstruktur und Bindungsart der praktisch brauchbaren Stoffe vertiefen müssen, um in planmäßiger Weise diejenigen chemischen Elemente zur Verbindungsbildung beizuziehen, die aus den allgemeinen Erkenntnissen über Bau, Größe und Bindungsvermögen der Atome in Betracht kommen und in Deutschland als Rohstoffe vorhanden sind.

[1] K. H. SCHEUMANN, Fortschr. d. Min. Krist. Petrographie 17, 69 (1937). — W. LÜTTGE, Fortschr. d. Min. Krist. Petrographie 18, 29 (1933); 15, 40 (1935). — Vgl. auch MACHATSCHKI, Naturwiss. 24, 742 (1936).

[2] W. NOLL, Naturwiss. 20, 283 (1932).

[3] W. NOLL, Naturwiss. 20, 366 (1932).

[4] W. NOLL, Naturwiss. 23, 197 (1935); vgl. auch W. NOLL, Ber. dtsch. keram. Ges. 19, H. 5 (1938).

Über den Nachweis und das Verhalten der bei der Bestrahlung des Urans mittels Neutronen entstehenden Erdalkalimetalle[1].

Von O. HAHN und F. STRASSMANN, Berlin-Dahlem.

In einer vor kurzem an dieser Stelle erschienenen vorläufigen Mitteilung[2] wurde angegeben, daß bei der Bestrahlung des Urans mittels Neutronen außer den von MEITNER, HAHN und STRASSMANN im einzelnen beschriebenen Trans-Uranen — den Elementen 93 bis 96 — noch eine ganze Anzahl anderer Umwandlungsprodukte entstehen, die ihre Bildung offensichtlich einem sukzessiven zweimaligen α-Strahlenzerfall des vorübergehend entstandenen Urans 239 verdanken. Durch einen solchen Zerfall muß aus dem Element mit der Kernladung 92 ein solches mit der Kernladung 88 entstehen, also ein Radium. In der genannten Mitteilung wurden in einem noch als vorläufig bezeichneten Zerfallsschema 3 derartiger isomerer Radiumisotope mit ungefähr geschätzten Halbwertszeiten und ihren Umwandlungsprodukten, nämlich drei isomeren Actiniumisotopen, angegeben, die ihrerseits offensichtlich in Thorisotope übergehen.

Zugleich wurde auf die zunächst unerwartete Beobachtung hingewiesen, daß diese unter α-Strahlenabspaltung über ein Thorium sich bildenden Radiumisotope nicht nur mit schnellen, sondern auch mit verlangsamten Neutronen entstehen.

Der Schluß, daß es sich bei den Anfangsgliedern dieser drei neuen isomeren Reihen um Radiumisotope handelt, wurde darauf begründet, daß diese Substanzen sich mit Bariumsalzen abscheiden lassen und alle Reaktionen zeigen, die dem Element Barium eigen sind. Alle anderen bekannten Elemente, angefangen von den Trans-Uranen über das Uran, Protactinium, Thorium bis zum Actinium haben andere chemische Eigenschaften als das Barium und lassen sich leicht von ihm trennen. Dasselbe trifft zu für die Elemente unterhalb Radium, also etwa Wismut, Blei, Polonium, Ekacäsium.

Es bleibt also, wenn man das Barium selbst außer Betracht läßt, nur das Radium übrig.

Im folgenden soll kurz die Abscheidung des Isotopengemisches und die Gewinnung der einzelnen Glieder beschrieben werden. Aus dem Aktivitätsverlauf der einzelnen Isotope ergibt sich ihre Halbwertszeit und lassen sich die daraus entstehenden Folgeprodukte ermitteln. Die letzteren werden in dieser Mitteilung aber im einzelnen noch nicht beschrieben, weil wegen der sehr komplexen Vorgänge — es handelt sich um mindestens 3, wahrscheinlich 4 Reihen mit je 3 Substanzen — die Halbwertszeiten aller Folgeprodukte bisher noch nicht erschöpfend festgestellt werden konnten.

Als Trägersubstanz für die „Radiumisotope" diente naturgemäß immer das Barium. Am nächstliegenden war die Fällung des Bariums als Bariumsulfat, das neben dem Chromat schwerstlösliche Bariumsalz. Nach früheren Erfahrungen und einigen Vorversuchen wurde aber von der Abscheidung der „Radiumisotope" mit Bariumsulfat abgesehen; denn diese Niederschläge reißen neben geringen Mengen Uran nicht unbeträchtliche Mengen von Actinium- und Thoriumisotopen mit, also auch die mutmaßlichen Umwandlungsprodukte der Radiumisotope, und erlauben daher keine Reindarstellung der Ausgangsglieder. Statt der quantitativen, sehr oberflächenreichen Sulfatfällung wurde daher das in starker Salzsäure sehr schwer lösliche Ba-Chlorid als Fällungsmittel gewählt; eine Methode, die sich bestens bewährt hat.

Bei der energetisch nicht leicht zu verstehenden Bildung von Radiumisotopen aus Uran beim Beschießen mit langsamen Neutronen war eine besonders gründliche Bestimmung des chemischen Charakters der neu entstehenden künstlichen Radioelemente unerläßlich. Durch die Abtrennung einzelner analytischer Gruppen von Elementen aus der Lösung des bestrahlten Urans wurde außer der großen Gruppe der Transurane eine Aktivität stets bei den Erdalkalien (Trägersubstanz Ba), den seltenen Erden (Trägersubstanz La) und bei Elementen der vierten Gruppe des Periodischen Systems (Trägersubstanz Zr) gefunden. Eingehender untersucht wurden zunächst die Bariumfällungen, die offensichtlich die Anfangsglieder der beobachteten isomeren Reihen enthielten. Es soll gezeigt werden, daß Transurane, Uran, Protactinium, Thorium und Actinium

[1] Aus dem Kaiser Wilhelm-Institut für Chemie in Berlin-Dahlem. Eingegangen 22. Dezember 1938.

[2] O. HAHN u. F. STRASSMANN, Naturwiss. 26, 756 (1938).

sich stets leicht und vollständig von der mit Barium ausfallenden Aktivität trennen lassen.

1. Zu diesem Zweck wurden aus einem bestrahlten Uran mittels Schwefelwasserstoff die Transurane mit Platinsulfid zusammen abgeschieden und in Königswasser gelöst. Aus dieser Lösung wurde Bariumchlorid mit Salzsäure gefällt. Aus dem Filtrat des Bariumniederschlages wurde das Platin nochmals mit Schwefelwasserstoff gefällt. *Das Bariumchlorid war inaktiv*, das Platinsulfid hatte noch eine Aktivität von ∾500 Teilchen/Minute. Entsprechende Versuche mit den langlebigeren Transuranen hatten das gleiche Ergebnis.

2. Eine Fällung von Bariumchlorid aus 10 g nichtbestrahltem Uranylnitrat, das im Gleichgewicht mit $UX_1 + UX_2$ (Thor- und Protactiniumisotope) war und eine Aktivität von ∾400000 Teilchen/Minute hat,

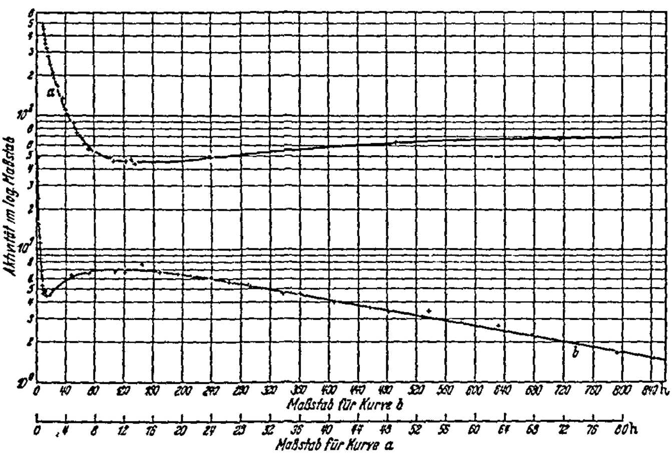

Fig. 1. Die drei Ra-Isotope nach langer Bestrahlung. a = Ra [4 Tage bestrahlt] über 70 Std. gemessen. b = obere Kurve im Maßstabe 1:10 über 800 Std. gemessen.

zeigte eine Aktivität von ∾14 Teilchen/Minute, war also ebenfalls praktisch inaktiv; d. h. weder Uran, noch Protactinium, noch Thorium fallen mit dem kristallisierenden Bariumchlorid aus.

3. Schließlich wurde noch aus der Lösung eines Actiniumpräparates ($MsTh_2$) von ∾2500 Teilchen pro Minute ein Bariumchloridniederschlag gefällt, der ∾3 Teilchen/Minute aufwies, also praktisch ebenfalls inaktiv war.

In ähnlicher Weise wurden die aus bestrahltem Uran gefällten stark aktiven Bariumchloridniederschläge sorgfältig geprüft, doch waren Sulfidniederschläge aus neutraler, schwach essigsaurer oder schwach mineralsaurer Lösung des aktiven Bariums praktisch inaktiv, während die Lanthan- und Zirkonfällungen nur Aktivitäten hatten, deren Entstehung aus der Aktivität der Bariumfällungen leicht nachgewiesen werden konnte.

Die einfache Fällung mit $BaCl_2$ aus stark salzsaurer Lösung gestattet natürlich keine Unterscheidung zwischen Barium und Radium. Nach diesen hier nur sehr summarisch aufgezählten Reaktionen kann die mit den Bariumsalzen abgeschiedene Aktivität nur von Radium herrühren, wenn man das Barium selbst als allzu unwahrscheinlich vorerst außer Betracht läßt.

Wir gehen jetzt kurz auf die mit Bariumchlorid erhaltenen Aktivitätskurven ein, die einerseits zu Aussagen über die Anzahl der „Radiumisotope" führen und außerdem deren Halbwertszeiten zu bestimmen erlauben.

Die Fig. 1 zeigt den Aktivitätsverlauf des aktiven *Bariumchlorids nach viertägiger Bestrahlung des Urans*. Die Kurve *a* gibt die Messungen über die ersten 70 Stunden; die Kurve *b* die Meßwerte für das gleiche Präparat über 800 Stunden fortgeführt. Der Maßstab der unteren Kurve ist zehnmal kleiner als der für die obere. Die anfänglich schnelle Abnahme wird allmählich langsamer und geht nach etwa 12 Stunden in eine langsame Zunahme über. Nach ungefähr 120 Stunden beginnt dann wieder eine sehr allmähliche Aktivitätsabnahme; sie erfolgt exponentiell mit einer Halbwertszeit von rund 13 Tagen.

Der Verlauf der Kurven zeigt deutlich, daß hier mehrere Substanzen vorliegen müssen. Man kann aber nicht ohne weiteres sagen, welches die Körper sind: ob mehrere „Radiumisotope" oder ein „Radiumisotop" mit einer Reihe von Folgeprodukten den Aktivitätsverlauf bestimmen.

Es sei hier gleich vorweggenommen, daß die schon in der ersten Mitteilung angegebenen drei isomeren „Radiumisotope" bestätigt wurden. Sie seien vorerst als Ra II und Ra III und Ra IV bezeichnet (wegen eines mutmaßlichen Ra I s. weiter unten).

Ihr Nachweis und die Ermittlung ihrer Halbwertszeiten wird an Hand der folgenden Figuren kurz dargestellt.

Die Fig. 2 bringt die Auswertung einer „Radium"-Abfallskurve nach 6 Minuten langer Bestrahlung des Urans.

Die Kurve *a* gibt die direkt gemessene Aktivität, 215 Minuten lang gemessen. Sie setzt sich zusammen aus der Aktivität von zwei „Radium"-Isotopen Ra II und Ra III (vgl. Fig. 3) und einer geringen Actiniumaktivität, die sich aus Ra II bildet. Diese als Ac II bezeichnete Substanz hat, wie andere Versuche, auf die hier nicht eingegangen wird, gezeigt haben, eine Halbwertszeit von etwa $2^1/_2$ Stunden. Die theoretische Zunahmekurve für ein solches aus Ra II entstehendes Actiniumisotop ist in der Figur als Kurve *b* wiedergegeben. Als Halbwertszeit für das Ra II ist dabei schon der Wert von 14 Minuten vorweggenommen. Zieht man die Werte der Kurve *b* von denen der Kurve *a* ab, dann ergibt sich die Kurve *c* der Figur. Diese Aktivität rührt nun praktisch nur noch von Radiumisotopen her, und zwar in der Hauptsache von dem kurzlebigen Ra II und in untergeordnetem Maße dem längerlebigen Ra III. Letzteres hat, wie sich weiter unten aus Fig. 3 ergibt, eine Halbwertszeit von ungefähr 86 Minuten. Den Aktivitätsverlauf von Ra III zeigt die Kurve *d* der

Fig. 2. Zieht man d von c ab, so erhält man schließlich in Kurve e die Aktivität des reinen Ra II. Die Abnahme erfolgt exponentiell mit einer Halbwertszeit von 14 Minuten. Dieser Wert dürfte sicher innerhalb $\pm$ 2 Minuten richtig sein.

Wir kommen nun zum Nachweis der Existenz und zur Bestimmung der Halbwertszeit von Ra III. Wird ein Uranpräparat eine Stunde oder ein paar Stunden lang bestrahlt, dann findet man außer der anfänglichen schnellen Aktivitätsabnahme eine sehr erhebliche Aktivität, die in etwa 100—110 Minuten zur Hälfte abklingt und schließlich noch langsamer wird. Um zu beweisen, daß diese Aktivität im wesentlichen ebenfalls einem Radiumisotop zuzuschreiben ist, wurde folgendermaßen vorgegangen. Aus dem bestrahlten Uranpräparat wurde das „Radium" mittels Bariumchlorid abgetrennt; $2^1/_2$ Stunden später wurde das Bariumchlorid wieder aufgelöst und erneut gefällt. Das kurzlebige Ra II ist in dieser Zeit vollständig zerfallen, und das aus dem Ra II in dem Bariumchlorid entstandene Ac II ($2^1/_2$ Stunden Halbwertszeit) wird bei der Umkristallisation des Bariumchlorids entfernt. Das Bariumchlorid ist noch erheblich aktiv, es liegt also noch ein „Radiumisotop" vor. Es wird hier also so vorgegangen, wie dies von MEITNER, STRASSMANN und HAHN schon bei der Aufklärung der aus dem Thorium entstehenden künstlichen Umwandlungsprodukte durchgeführt worden war[1]. Der nunmehr erhaltene Aktivitätsverlauf ist in Fig. 3, Kurve a wiedergegeben.

Die Abnahme erfolgt während der ersten Stunden fast rein exponentiell mit $\sim$86 Minuten Halbwertszeit, eine kleine Restaktivität bleibt übrig. Sie besteht wohl zweifellos aus einem aus dem Ra III sich bildenden langlebigen „Actiniumisotop", dessen mutmaßlicher Aktivitätsverlauf sich aus der Abweichung der Kurve a von einem rein exponentiellen Zerfall ungefähr erschließen läßt. Die dabei erhaltene Aktivitätskurve ist als Kurve b in der Fig. 3 wiedergegeben. (Daß bei dem Zerfall des Ra III ein „Actiniumisotop" von verhältnismäßig langer Lebensdauer entsteht, wurde auch chemisch nachgewiesen.) Zieht man b von a ab, so erhält man die Kurve c für das nunmehr reine Ra III. Sie zeigt einen sehr schönen exponentiellen Abfall mit einer Halbwertszeit von 86 Minuten. Dieser Wert dürfte wohl innerhalb $\pm$ 6 Minuten richtig sein.

Wir kommen jetzt noch zu dem dritten, hier als Ra IV bezeichneten „Radiumisotop". Der spätere Verlauf der Kurve b in Fig. 1 ergab eine mit etwa 12 bis 13 Tagen Halbwertszeit zerfallende Substanz. Daß diese langsamere Aktivitätsabnahme im wesentlichen von einem „Radiumisotop" herrührt, wurde auf ganz ähnliche Weise bewiesen wie beim Ra III. Läßt man ein lange bestrahltes Uran nach der Entfernung von der Neutronenquelle etwa einen Tag stehen, dann zerfallen die Isotope Ra II und Ra III vollständig. Macht man jetzt eine Bariumfällung, kristallisiert vorsichtshalber noch einmal um, dann kann eine beim Bariumchlorid gefundene Aktivität nur noch von einem weiteren „Radiumisotop" herrühren. Derartige Aktivitäten wurden, auch nach tagelangem Stehen, immer gefunden. Ihr Aktivitätsverlauf ist sehr charakteristisch. Die Aktivität nimmt während mehrerer Tage allmählich zu, erreicht ein Maximum und verschwindet dann mit einer Halbwertszeit von rund 300 Stunden (12,5 Tage).

In der Fig. 4 sind einige solcher Kurven wiedergegeben. Das Präparat der Kurve c war aus einem unverstärkt bestrahlten Uranpräparat abgetrennt, die

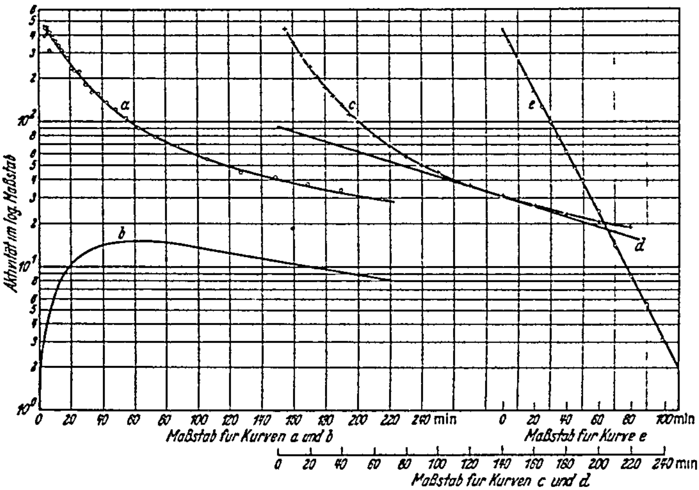

Fig. 2. Bestimmung der Halbwertszeit von Ra II (kurze Bestrahlung). a = Ra nach 6 Min. Bestrahlung. Direkte Abfallskurve. b = theoret. Zunahmekurve d. 2,5-Std.-Ac aus Ra II, H. Z. = 14 Min. $c = a$ [Ra] — b [Zunahme 2,5 Std.] d = Ra III, H. Z. = 86 Min. $e = c - d$ = Ra II, ergibt 14 Min. H. Z.

anderen Kurven beziehen sich auf entsprechende Bariumfällungen aus verstärkt bestrahltem Uran. (Über den Verstärkungsfaktor läßt sich aus den Kurven nichts aussagen, weil hier nicht unter gleichen geometrischen Bedingungen gearbeitet wurde. Bei gleichen Bedingungen, gleicher bestrahlter Uranmenge usw., fanden wir einen Verstärkungsfaktor von rund 7.) Der Verlauf der 3 Kurven ist sehr ähnlich. Die Zunahme der Aktivität erfolgt mit einer Halbwertszeit von weniger als 40 Stunden, die Abnahme mit rund 300 Stunden. Zweifellos ist die Halbwertszeit dieses langlebigen „Ra IV" aber etwas kurzer als 300 Stunden, denn außer der für die anfängliche Zunahme im wesentlichen verantwortlichen Entstehung von Ac IV aus Ra IV entsteht aus dem Ac IV wohl noch ein langlebiges „Thorisotop", so daß die Halbwertszeit des Ra IV nicht ganz genau festgelegt ist. Ein Wert von 250—300 Stunden wird wohl der Wahrheit nahe kommen. Aus den Kurven a, b und c sieht man auch deutlich, daß die β-Strahlung des Ra IV wesentlich absorbierbarer ist als die seiner Folgeprodukte, sonst könnte kein so starker Anstieg erfolgen.

[1] L. MEITNER, F. STRASSMANN u. O. HAHN, Z. Physik 109, 538 (1938).

Die im vorhergehenden gebrachten Ergebnisse zusammenfassend haben wir also drei als Ra II, Ra III und Ra IV bezeichnete isomere Erdalkalimetalle festgestellt. Ihre Halbwertszeiten sind 14 ± 2 Minuten, *86 ± 6 Minuten, 250—300 Stunden*. Es wird aufgefallen sein, daß der 14-Minuten-Körper nicht als Ra I, die weiteren Isomeren nicht als Ra II und Ra III bezeichnet worden sind. Der Grund liegt darin, daß wir an ein noch instabileres „Ra" glauben, obgleich es bisher nicht nachgewiesen wurde. In unserer ersten Mitteilung über die neuen Umwandlungsprodukte haben wir ein Actinium von etwa 40 Minuten Halbwertszeit angegeben und

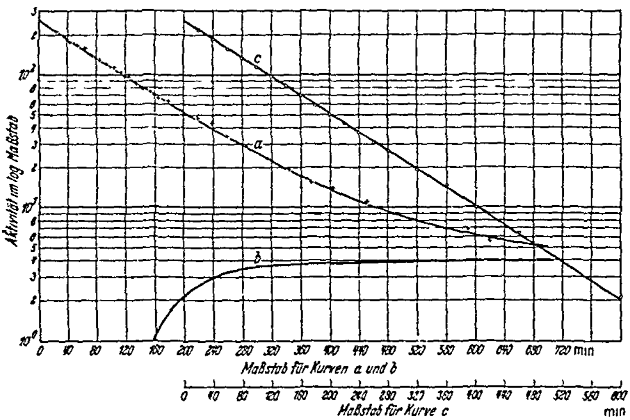

Fig. 3. Bestimmung der Halbwertszeit von Ra III nach 2,5-stündiger Bestrahlung. a = Ra III [2,5 Std. bestrahlt]. 3 Std n. Bestr. wurde Ac abgetrennt. b = ∾ Zunahmekurve v. langem Ac aus Ra III v. 86 Min. H.Z. $c = a - b$ = Ra III. H Z. = ∾ 86 Min.

als nächstliegende Annahme die gemacht, daß dieses instabilste Actiniumisotop aus dem instabilsten Radiumisotop entsteht. Nun haben wir in der Zwischenzeit festgestellt, daß das aus dem 14-Minuten-Radium (früher 25 Minuten) entstehende „Actinium" eine ungefähre Halbwertszeit von 2,5 Stunden hat (früher mit 4 Stunden angegeben). Das obenerwähnte instabilere Actiniumisotop ist aber ebenfalls vorhanden. Seine Halbwertszeit ist etwas kleiner als früher angegeben, — wohl unter 30 Minuten. Da dieses „Actiniumisotop" weder aus dem 14-Minuten-, noch aus dem 86-Minuten-Körper, noch aus dem langlebigen „Ra" entstehen kann, — da außerdem dieses „Actiniumisotop" schon nach 5 Minuten langer Bestrahlung des Urans nachweisbar ist, ist die einfachste Annahme für seine Entstehung ein „Radiumisotop", dessen Halbswertszeit kürzer als 1 Minute sein muß. Mit einer größeren Halbwertszeit als eine Minute hätten wir es nämlich nachweisen müssen; wir haben sehr danach gesucht. Wir bezeichnen deshalb diese bisher unbekannte, mit einer stärkeren Strahlenquelle wohl zweifellos nachweisbare Muttersubstanz des instabilsten „Actiniumisotops" als „Ra I".

Das in unserer ersten Mitteilung gebrachte Schema muß dadurch eine gewisse Korrektur erfahren. Das folgende Schema trägt dieser Änderung Rechnung und gibt für die Anfangsglieder der Reihen die nunmehr genauer bestimmten Halbwertszeiten:

$$\text{„Ra I"?} \xrightarrow[<1\,\text{Min.}]{\beta} \text{Ac I} \xrightarrow[<30\,\text{Min.}]{\beta} \text{Th?}$$

$$\text{„Ra II"} \xrightarrow[14\pm2\,\text{Min.}]{\beta} \text{Ac II} \xrightarrow[\sim 2{,}5\,\text{Std.}]{\beta} \text{Th?}$$

$$\text{„Ra III"} \xrightarrow[86\pm6\,\text{Min.}]{\beta} \text{Ac III} \xrightarrow[\sim\text{mehrere Tage?}]{\beta} \text{Th?}$$

$$\text{„Ra IV"} \xrightarrow[250-300\,\text{Std}]{\beta} \text{Ac IV} \xrightarrow[<40\,\text{Std.}]{\beta} \text{Th?}$$

Die große Gruppe der „Transurane" steht bisher in keinem erkennbaren Zusammenhang mit diesen Reihen.

Die in dem vorliegenden Schema mitgeteilten Umwandlungsreihen sind in ihren *genetischen* Beziehungen wohl zweifellos als richtig anzusehen. Von den am Ende der isomeren Reihen als „Thorium" angegebenen Endgliedern haben wir auch schon einige nachweisen können. Aber da über ihre einzelnen Halbwertszeiten noch keine genauen Angaben gemacht werden können, haben wir bei ihnen vorerst überhaupt auf eine Angabe verzichtet.

Nun müssen wir aber noch auf einige neuere Untersuchungen zu sprechen kommen, die wir der seltsamen Ergebnisse wegen nur zögernd veröffentlichen. Um den Beweis für die chemische Natur der mit dem Barium abgeschiedenen und als „Radiumisotope" bezeichneten Anfangsglieder der Reihen über jeden Zweifel hinaus zu erbringen, haben wir mit den aktiven Bariumsalzen fraktionierte Kristallisationen und fraktionierte Fällungen vorgenommen, in der Weise, wie sie für die Anreicherung (oder auch Abreicherung) des Radiums in Bariumsalzen bekannt sind.

Bariumbromid reichert das Radium bei fraktionierter Kristallisation stark an, Bariumchromat bei nicht zu schnellem Herauskommen der Kriställchen noch mehr. Bariumchlorid reichert weniger stark an als das Bromid, Bariumkarbonat reichert etwas ab. Entsprechende Versuche, die wir mit unseren von Folgeprodukten gereinigten aktiven Bariumpräparaten gemacht haben, *verliefen ausnahmslos negativ: Die Aktivität blieb gleichmäßig auf alle Bariumfraktionen verteilt*, wenigstens soweit wir dies innerhalb der nicht ganz geringen Versuchsfehlermöglichkeiten angeben können. Es wurden dann ein paar Fraktionierungsversuche mit dem Radiumisotop ThX und mit dem Radiumisotop $MsTh_1$ gemacht. Sie verliefen genau so, wie man aus allen früheren Erfahrungen mit dem Radium erwarten sollte. Es wurde dann die „Indikatorenmethode" auf ein Gemisch des gereinigten langlebigen „Ra IV" mit reinem, radiumfreien $MsTh_1$ angewandt: das Gemisch mit Bariumbromid als Trägersubstanz wurde fraktioniert kristallisiert. *Das $MsTh_1$ wurde angereichert, das „Ra IV" nicht*, sondern seine Aktivität blieb bei gleichem Bariumgehalt der Fraktionen wieder gleich. Wir kommen zu dem Schluß: Unsere „Radiumisotope" haben die Eigenschaften des Bariums; als Chemiker müßten wir eigentlich sagen, bei den neuen Körpern handelt es sich nicht um Radium, sondern um Barium;

denn andere Elemente als Radium oder Barium kommen nicht in Frage.

Schließlich haben wir auch einen Indikatorversuch mit unserem rein abgeschiedenen „AcII" (H.Z. rund 2,5 Stunden) und dem reinen Actiniumisotop $MsTh_2$ gemacht. Wenn unsere „Ra-Isotope" kein Radium sind, dann sind die „Ac-Isotope" auch kein Actinium, sondern sollten Lanthan sein. Nach dem Vorgehen von Mme CURIE[1] haben wir *eine Fraktionierung von* Lanthanoxalat, das die beiden aktiven Substanzen enthielt, aus salpetersaurer Lösung vorgenommen. Das $MsTh_2$ fand sich, wie von Mme CURIE angegeben, in den Endfraktionen stark angereichert. Bei unserem „Ac II" war von einer Anreicherung am Ende nichts zu merken. In Übereinstimmung mit CURIE und SAVITCH[2] über ihren allerdings nicht einheitlichen 3,5-Stunden-Körper finden wir also, daß das aus unserem aktiven Erdalkalimetall durch β-Strahlenemission entstehende Erdmetall kein Actinium ist. Den von CURIE und SAVITCH angegebenen Befund, daß sie die Aktivität im Lanthan anreicherten, der also gegen eine *Gleichheit mit Lanthan* spricht, wollen wir noch genauer experimentell prüfen, da bei dem dort vorliegendem Gemisch eine Anreicherung vorgetäuscht sein könnte.

Ob die aus den „Ac-La-Präparaten" entstehenden, als „Thor" bezeichneten Endglieder unserer Reihen sich als Cer *herausstellen*, wurde noch *nicht* geprüft.

Was die „Trans-Urane" anbelangt, so sind diese Elemente ihren niedrigeren Homologen Rhenium, Osmium, Iridium, Platin zwar chemisch verwandt, mit ihnen aber nicht gleich. Ob sie etwa mit den noch niedrigeren Homologen Masurium, Ruthenium, Rhodium, Palladium chemisch gleich sind, wurde noch nicht geprüft. Daran konnte man früher ja nicht denken. Die Summe der Massenzahlen Ba + Ma, also z. B. 138 + 101, ergibt 239!

[1] Mme PIERRE CURIE, J. Chim. physique etc. 27, 1 (1930).

[2] I. CURIE u. P. SAVITCH, C. r. Acad. Sci. Paris 206, 1643 (1938).

Als Chemiker müßten wir aus den kurz dargelegten Versuchen das oben gebrachte Schema eigentlich umbenennen und statt Ra, Ac, Th die Symbole Ba, La, Ce einsetzen. Als der Physik in gewisser Weise nahestehende „Kernchemiker" können wir uns zu diesem, allen bisherigen Erfahrungen der Kernphysik widersprechenden, Sprung noch nicht entschließen. Es könnten doch noch vielleicht eine Reihe seltsamer Zufälle unsere Ergebnisse vorgetäuscht haben.

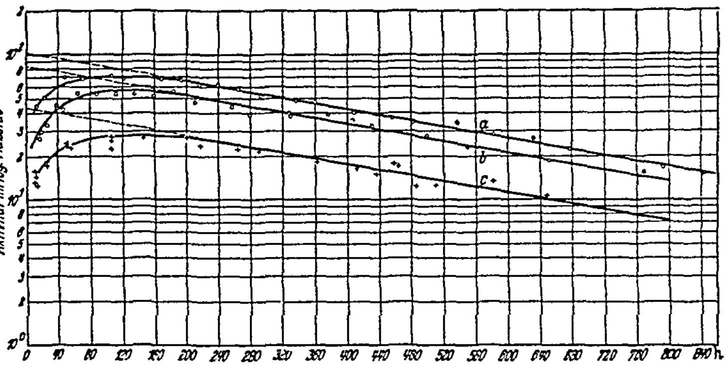

Fig. 4. Bestimmung der Halbwertszeit von Ra IV bei verschiedener Bestrahlungszeit und -art.

a = Ra IV [∼4 Tage bestrahlt] } verstärkt,
b = Ra IV [∼2,6 „ „] } ←------→ Ra-Abtrennung 15 Std. nach Ende der Bestrahlung,
c = Ra IV [∼2,6 „ „] unverstärkt,

a H.Z. = ∼311 Stunden, b H.Z. = ∼310 Stunden, c H.Z. = ∼300 Stunden.

Es ist beabsichtigt, weitere Indikatorenversuche mit den neuen Umwandlungsprodukten durchzuführen. Insbesondere soll auch *eine* gemeinsame Fraktionierung der aus Thor durch Bestrahlen mit schnellen Neutronen entstehenden, von MEITNER, STRASSMANN und HAHN[1] untersuchten Radiumisotope mit unseren aus dem Uran entstandenen Erdalkalimetallen versucht werden. An Stellen, denen starke künstliche Strahlenquellen zur Verfügung stehen, könnte dies allerdings wesentlich leichter geschehen.

Zum Schlusse danken wir Frl. CL. LIEBER und Frl. I. BOHNE für ihre wirksame Hilfe bei den sehr zahlreichen Fällungen und Messungen.

[1] L. MEITNER, F. STRASSMANN u. O. HAHN, l. c.

Besprechungen.

STUBBE, H., Spontane und strahleninduzierte Mutabilität. (Probleme der theoretischen und angewandten Genetik und deren *Grenzgebiete*, redigiert von W. F. REINIG.) Leipzig: Georg Thieme 1937. 190 S. und 12 Abbild. 13 cm × 21 cm. *Preis kart. RM 6.80.*

Nach 10 Jahren emsiger Arbeit hat die experimentelle Mutationsforschung heute ein Stadium erreicht, das dazu berechtigt, die Ergebnisse dieser Forschungen zusammenfassend darzustellen und einem größeren Leserkreis näherzubringen. Nachdem erst kürzlich von TIMOFÉEFF-RESSOVSKY eine Darstellung der experimentellen Mutationsforschung gegeben wurde, behandelt STUBBE dieses Gebiet in den „Problemen der Genetik". Er versucht, sich auf die spontane und die strahleninduzierte Mutabilität zu beschränken, doch ergeben sich verschiedene Schwierigkeiten, wenn *man die spontane Mutabilität behandeln will*, ohne auf die Frage der Abhängigkeit der Mutationsrate von verschiedenen physiologischen Bedingungen einzugehen. Wenn auch erst wenig brauchbare Ergebnisse auf diesem Gebiet vorliegen, so kann doch an den hier aufgeworfenen Problemen nicht vorbeigegangen werden. Sie werden denn auch vom Verf. angeschnitten bei der Behandlung der Abhängigkeit der „Mutationsrate"

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THE PRODUCTION OF HIGH SPEED LIGHT IONS WITHOUT THE USE OF HIGH VOLTAGES

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Abstract

The study of the nucleus would be greatly facilitated by the development of sources of high speed ions, particularly protons and helium ions, having kinetic energies in excess of 1,000,000 volt-electrons; for it appears that such swiftly moving particles are best suited to the task of nuclear excitation. The straightforward method of accelerating ions through the requisite differences of potential presents great experimental difficulties associated with the high electric fields necessarily involved. The present paper reports the development of a method that avoids these difficulties by means of the multiple acceleration of ions to high speeds without the use of high voltages. The method is as follows: Semi-circular hollow plates, not unlike duants of an electrometer, are mounted with their diametral edges adjacent, in a vacuum and in a uniform magnetic field that is normal to the plane of the plates. High frequency oscillations are applied to the plate electrodes producing an oscillating electric field over the diametral region between them. As a result during one half cycle the electric field accelerates ions, formed in the diametral region, into the interior of one of the electrodes, where they are bent around on circular paths by the magnetic field and eventually emerge again into the region between the electrodes. The magnetic field is adjusted so that the time required for traversal of a semi-circular path within the electrodes equals a half period of the oscillations. In consequence, when the ions return to the region between the electrodes, the electric field will have reversed direction, and the ions thus receive second increments of velocity on passing into the other electrode. Because the path radii within the electrodes are proportional to the velocities of the ions, the time required for a traversal of a semi-circular path is independent of their velocities. Hence if the ions take exactly one half cycle on their first semi-circles, they do likewise on all succeeding ones and therefore spiral around in resonance with the oscillating field until they reach the periphery of the apparatus. Their final kinetic energies are as many times greater than that corresponding to the voltage applied to the electrodes as the number of times they have crossed from one electrode to the other. This method is primarily designed for the acceleration of light ions and in the present experiments particular attention has been given to the production of high speed protons because of their presumably unique utility for experimental investigations of the atomic nucleus. Using a magnet with pole faces 11 inches in diameter, a current of 10^{-9} ampere of 1,220,000 volt-protons has been produced in a tube to which the maximum applied voltage was only 4000 volts. There are two features of the developed experimental method which have contributed largely to its success. First there is the focussing action of the electric and magnetic fields which prevents serious loss of ions as they are accelerated. In consequence of this, the magnitudes of the high speed ion currents obtainable in this indirect manner are comparable with those conceivably obtainable by direct high voltage methods. Moreover, the focussing action results in the generation of very narrow beams of ions—less than 1 mm cross-sectional diameter—which are ideal for experimental studies of collision processes. Of hardly less importance is the second feature of the method which is the simple and highly effective means for the correction of the magnetic field along the paths of the ions. This makes it possible, indeed easy, to operate the tube effectively

with a very high amplification factor (i.e., ratio of final equivalent voltage of accelerated ions to applied voltage). In consequence, this method in its present stage of development constitutes a highly reliable and experimentally convenient source of high speed ions requiring relatively modest laboratory equipment. Moreover, the present experiments indicate that this indirect method of multiple acceleration now makes practicable the production in the laboratory of protons having kinetic energies in excess of 10,000,000 volt-electrons. With this in mind, a magnet having pole faces 114 cm in diameter is being installed in our laboratory.

Introduction

THE classical experiments of Rutherford and his associates[1] and Pose[2] on artificial disintegration, and of Bothe and Becker[3] on excitation of nuclear radiation, substantiate the view that the nucleus is susceptible to the same general methods of investigation that have been so successful in revealing the extra-nuclear properties of the atom. Especially do the results of their work point to the great fruitfulness of studies of nuclear transitions excited artificially in the laboratory. The development of methods of nuclear excitation on an extensive scale is thus a problem of great interest; its solution is probably the key to a new world of phenomena, the world of the nucleus.

But it is as difficult as it is interesting, for the nucleus resists such experimental attacks with a formidable wall of high binding energies. Nuclear energy levels are widely separated and, in consequence, processes of nuclear excitation involve enormous amounts of energy—millions of volt-electrons.

It is therefore of interest to inquire as to the most promising modes of nuclear excitation. Two general methods present themselves; excitation by absorption of radiation (gamma radiation), and excitation by intimate nuclear collisions of high speed particles.

Of the first it may be said that recent experimental studies [4,5] of the absorption of gamma radiation in matter show, for the heavier elements, variations with atomic number that indicate a quite appreciable nuclear effect. This suggests that nuclear excitation by absorption of radiation is perhaps a not infrequent process, and therefore that the development of an intense artificial source of gamma radiation of various wave-lengths would be of considerable value for nuclear studies. In our laboratory, as elsewhere, this being attempted.

But the collision method appears to be even more promising, in consequence of the researches of Rutherford and others cited above. Their pioneer investigations must always be regarded as really great experimental achievements, for they established definite and important information about nuclear processes of great rarity excited by exceedingly weak beams of bombarding particles—alpha-particles from radioactive sources. Moreover, and this is the point to be emphasized here, their work has shown strikingly the

[1] See Chapter 10 of Radiations from Radioactive Substances by Rutherford, Chadwick and Ellis.

[2] H. Pose, Zeits. f. Physik 64, 1 (1930).

[3] W. Bothe and H. Becker, Zeits. f. Physik 66, 1289 (1930).

[4] G. Beck, Naturwiss. 18, 896 (1930).

[5] C. Y. Chao, Phys. Rev. 36, 1519 (1930).

great fruitfulness of the kinetic collision method and the importance of the development of intense artificial sources of alpha-particles. Of course it cannot be inferred from their experiments that alpha-particles are the most effective nuclear projectiles: the question naturally arises whether lighter or heavier particles of given kinetic energy would be more effective in bringing about nuclear transitions.

A beginning has been made on the theoretical study of the nucleus and a partial answer to this question has been obtained. Gurney and Condon[6] and Gamow[7] have independently applied the ideas of the wave mechanics to radioactivity with considerable success. Gamow[8] has further considered along the same lines the penetration into the nucleus of swiftly moving charged particles (with excitation of nuclear transitions in mind) and has concluded that, for a given kinetic energy, the lighter the particle the greater is the probability that it will penetrate the nuclear potential wall. This result is not unconnected with the smaller momentum and consequent longer wavelength of the ligher particles; for it is well-known that transmission of matter waves through potential barriers becomes greater with increasing wavelengths.

If the probability of nuclear excitation by a charged particle were mainly dependent on its ability to penetrate the nuclear potential wall, electrons would be the most effective. However, there is considerable evidence that nuclear excitation by electrons is negligible. It suffices to mention here the current view that the average density of the extra-nuclear electrons is quite great in the region of the nucleus, i.e., that the nucleus is quite transparent to electrons; in other words, there are no available stable energy levels for them.

On the other hand, there is evidence that there are definite nuclear levels for protons as well as alpha-particles;[9] indeed, there is some justification for the view that the general principles of the quantum mechanics are applicable in the nucleus to protons and alpha particles. It is not possible at the present time to estimate the relative excitation probabilities of the protons and alpha particles that succeed in penetrating the nucleus. However, it does seem likely that the greater penetrability of the proton* is an advantage outweighing any differences in their excitation characteristics. Protons thus appear to be most suited to the task of nuclear excitation.

Though at present the relative efficacy of protons and alpha-particles cannot be established with much certainty, it does seem safe to conclude at least that the most efficacious nuclear projectiles will prove to be swiftly moving ions, probably of low atomic number. In consequence it is important to develop methods of accelerating ions to speeds much greater than have heretofore been produced in the laboratory.

[6] Gurney and Condon, Phys. Rev. 33, 127 (1929).
[7] Gamow, Zeits. f. Physik 51, 204 (1928).
[8] Gamow, Zeits. f. Physik 52, 514 (1929).
[9] J. Chadwick, J. E. R. Constable, E. C. Pollard, Proc. Roy. Soc. A130, 463 (1930).
* According to Gamow's theory a one million volt-proton has as great a penetrating power as a sixteen million volt alpha-particle.

The importance of this is generally recognized and several laboratories are developing techniques of the production and the application to vacuum tubes of high voltages for the generation of high speed electrons and ions. Highly significant progress in this direction has been made by Coolidge,[10] Lauritsen,[11] Tuve, Breit, Hafstad, Dahl,[12] Brasch and Lange,[13] Cockroft and Walton,[14] Van de Graaff[15] and others, who have developed several distinct techniques which have been applied to voltages of the order of magnitude of one million.

These methods involving the direct utilization of high voltages are subject to certain practical limitations. The experimental difficulties go up rapidly with increasing voltage; there are the difficulties of corona and insulation and also there is the problem of design of suitable high voltage vacuum tubes.

Because of these difficulties we have thought it desirable to develop methods for the acceleration of charged particles that do not require the use of high voltages. Our objective is two fold: first, to make the production of particles having kinetic energies of the order of magnitude of one million volt-electrons a matter that can be carried through with quite modest laboratory equipment and with an experimental convenience that, it is hoped, will lead to a widespread attack on this highly important domain of physical phenomena; and second, to make practicable the production of particles having kinetic energies in excess of those producible by direct high voltage methods—perhaps in the range of 10,000,000 volt-electrons and above.

A method for the multiple acceleration of ions to high speeds, primarily designed for heavy ions, has recently been described in this journal.[16] The present paper is a report of the development of a method for the multiple acceleration of light ions.[17] Particular attention has been given to the acceleration of protons because of their apparent unique utility in nuclear studies. In the present work relatively large currents of 1,220,000 volt-protons have been generated and there is foreshadowed in the not distant future the production of 10,000,000 volt-protons.

The Experimental Method

In the method for the multiple acceleration of ions to high speeds, recently described,[16] the ions travel through a series of metal tubes in synchronism with an applied oscillating electric potential. It is so arranged that as an

[10] W. D Collidge, Am. Inst. E. Eng 47, 212 (1928).

[11] C. C. Lauritsen and R. D. Bennett, Phys. Rev 32, 850 (1928)

[12] M. A. Tuve, G. Breit, L. R Hafstad and O. Dahl, Phys Rev. 35, 66 (1930); M. A. Tuve, L. R. Hafstad, O. Dahl, Phys. Rev. 39, 384, (1932).

[13] A. Brasch and J. Lange, Zeits. f. Physik 70, 10 (1931).

[14] J. J. Cockroft and E. T. S. Walton, Proc Roy. Soc. A129, 477 (1930).

[15] R. S Van de Graaff, Schenectady Meeting American Physical Society, 1931.

[16] D. H. Sloan and E. O. Lawrence, Phys. Rev. 38, 2021 (1931).

[17] This method was first described before the September, 1930, meeting of the National Academy of Sciences (Lawrence and Edlefsen, Science 72, 376–377 (1930)). Later before the American Physical Society (Lawrence and Livingston, Phys. Rev. 37, 1707, (1931)) results of a preliminary study of the practicability of the method were given. Further work was reported in a Letter to the Editor of the Physical Review (Lawrence and Livingston, Phys. Rev. 38, 834 (1931)

ion travels from the interior of one tube to the interior of the next there is always an accelerating field, and the final velocity of the ion on emergence from the system corresponds approximately to a voltage as many times greater than the applied voltage between adjacent tubes as there are tubes. The method is most conveniently used for the acceleration of heavy ions; for light ions travel faster and hence require longer systems of tubes for any given frequency of applied oscillations.

The present experimental method makes use of the same principle of repeated acceleration of the ions by a similar sort of resonance with an oscillating electric field, but has overcome the difficulty of the cumbersomely long accelerating system by causing, with the aid of a magnetic field, the ions to circulate back and forth from the interior of one electrode to the interior of another.

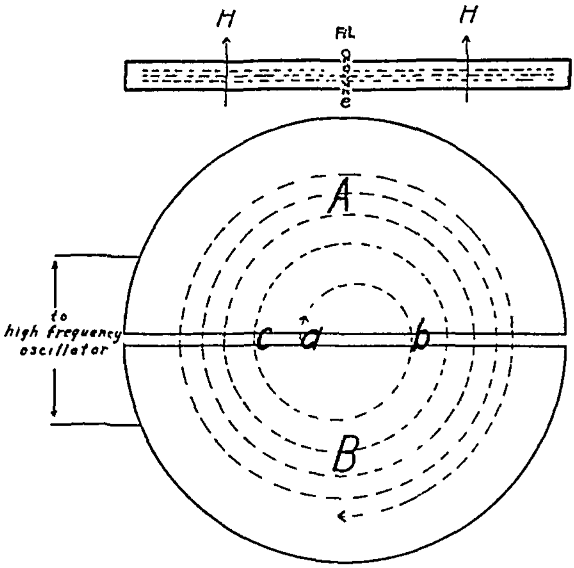


Fig. 1. Diagram of experimental method for multiple acceleration of ions.

This may be seen most readily by an outline of the experimental arrangement (Fig. 1). Two electrodes A, B in the form of semi-circular hollow plates are mounted in a vacuum tube in coplanar fashion with their diametral edges adjacent. By placing the system between the poles of a magnet, a magnetic field is introduced that is normal to the plane of the plates. High frequency electric oscillations are applied to the plates so that there results an oscillating electric field in the diametral region between them.

With this arrangement it is evident that, if at one moment there is an ion in the region between the electrodes, and electrode A is negative with respect to electrode B, then the ion will be accelerated to the interior of the former. Within the electrode the ion traverses a circular path because of the magnetic field, and ultimately emerges again between the electrodes; this is indicated in the diagram by the arc a .. b. If the time consumed by the ion in making the

semi-circular path is equal to the half period of the electric oscillations, the electric field will have reversed and the ion will receive a second acceleration passing into the interior of electrode B with a higher velocity. Again it travels on a semi-circular path ($b .. c$), but this time the radius of curvature is greater because of the greater velocity. For all velocities (neglecting variation of mass with velocity) the radius of the path is proportional to the velocity, so that the time required for traversal of a semi-circular path is independent of the ion's velocity. Therefore, if the ion travels its first half circle in a half cycle of the oscillations, it will do likewise on all succeeding paths. Hence it will circulate around on ever widening semi-circles from the interior of one electrode to the interior of the other, gaining an increment of energy on each crossing of the diametral region that corresponds to the momentary potential difference between the electrodes. Thus, if, as was done in the present experiments high frequency oscillations having peak values of 4000 volts are applied to the electrodes, and protons are caused to spiral around in this way 150 times, they will receive 300 increments of energy, acquiring thereby a speed corresponding to 1,200,000 volts.

It is well to recapitulate these remarks in quantitative fashion. Along the circular paths within the electrodes the centrifugal force of an ion is balanced by the magnetic force on it, i.e., in customary notation,

$$\frac{mv^2}{r} = \frac{Hev}{c} \tag{1}$$

It follows that the time for traversal of a semi-circular path is

$$t = \frac{\pi r}{v} = \frac{\pi mc}{He} \tag{2}$$

which is independent of the radius r of the path and the velocity v of the ion. The particle of mass m and charge e thus may be caused to travel in phase with the oscillating electric field by suitable adjustment of the magnetic field H: the relation between the wave-length λ of the oscillations and the corresponding synchronizing magnetic field H is in consequence

$$\lambda = \frac{2\pi mc^2}{He} \tag{3}$$

Thus for protons and a magnetic field of 10,000 gauss the corresponding wave-length is 19.4 meters; for heavier particles the proper wave-length is proportionately longer.*

It is easily shown also that the energy V in volt-electrons of the charged particles arriving at the periphery of the apparatus on a circle of radius r is

* It should be mentioned that, for a given wave-length, the ions resonate with the oscillations when magnetic fields of 1/3, 1/5, etc., of that given by Eq. (3) are used. Such types of resonance were observed in the earlier experimental studies. In the present experiments, however, the high speed ions resulting from the primary type of resonance only were able to pass through the slit system to the collector, because of the high deflecting voltages used.

$$V = 150 \frac{H^2 r^2}{c^2} \frac{e}{m} \tag{4}$$

Thus, the theoretical maximum producible energy varies as the square of the radius and the square of the magnetic field.

Experimental Arrangement

The experimental arrangement is shown diagrammatically in some detail in Fig. 2. Fig. 3 is a photograph of the brass vacuum tube with cover removed showing the filament, the accelerating electrode, the deflecting plates and slit system, the probe in front of the first slit mounted on a ground joint and the Faraday collector behind the last slit. An external view of the apparatus is shown in Fig. 4. Here the tube is shown between the magnet pole faces, connected with the oscillator, the vacuum system and hydrogen generator. This gives a good general idea of the modest extent of the equipment involved for the generation of protons having energies somewhat in excess of 1,000,000 volt-electrons. The control panel and electrometer, being on the other side, are not shown in the picture. The description of the apparatus follows.

The accelerating system. Though there are obvious advantages in applying the high frequency potentials with respect to ground to both accelerating electrodes, in the present experiments it was found convenient to apply the high frequency voltage to only one of the electrodes, as indicated in Fig. 2. This electrode was a semi-circular hollow brass plate 24 cm in diameter and 1 cm thick. The sides of the hollow plate were of thin brass so that the interior of the plate had approximately these dimensions. It was mounted on a water-cooled copper re-entrant tube which in turn passed through a copper to glass seal. The electrode insulated in this way was mounted in an evacuated brass box having internal dimensions 2.6 cm by 28.6 cm by 28.6 cm, there being thus a lateral clearance between the electrode and walls of the brass chamber of 8 mm.

The brass box itself constituted the other electrode of the accelerating system. Across the mid-section of the brass chamber parallel to the diametral edge of the electrode *A* was placed a brass dividing wall *S* with slits of the same dimensions as the opening of the nearby electrode. This arrangement gave rise to the same type of oscillating electric fields as would have been produced had there been used two insulated semi-circular electrodes with their diametral edges adjacent and parallel.

The source of ions. An ideal source of ions is one that delivers to the diametral region between the electrodes large quantities of ions with low components of velocity normal to the plane of the accelerators. This requirement has most conveniently been met in the present experiments merely by having a filament placed above the diametral region from which a stream of electrons pass down along the magnetic lines of force, generating ions of gases in the tube. The ions so formed are pulled out sideways by the oscillating electric field. The electrons are not drawn out because of their very small radii of curvature in the magnetic field. Thus, the beam of electrons is col-

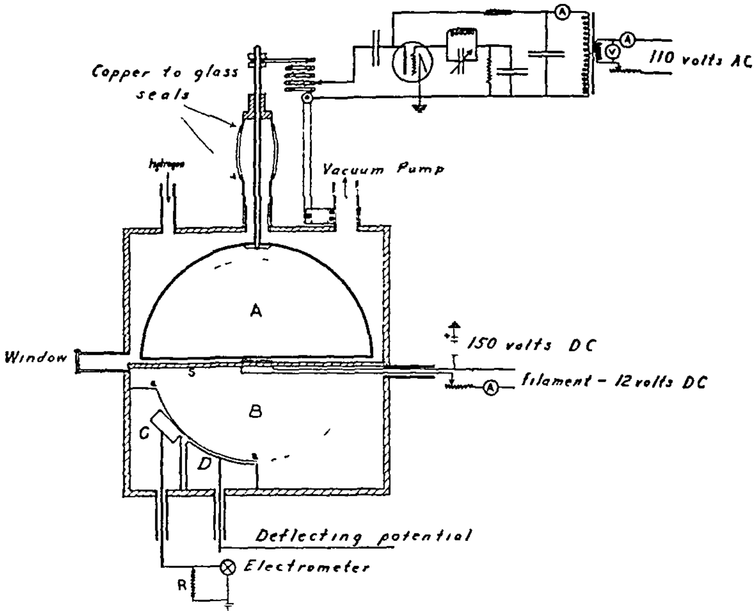


Fig 2 Diagram of apparatus for the multiple acceleration of ions.

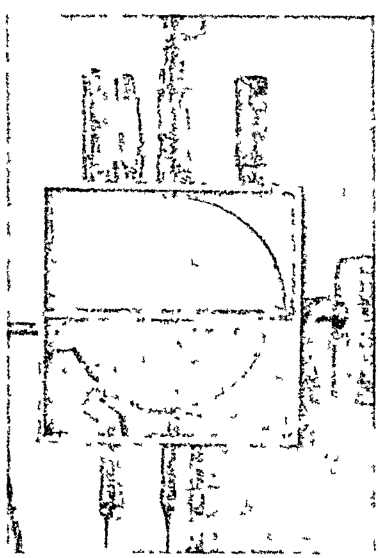


Fig. 3. Tube for the multiple acceleration of light ions—with cover removed.

limated and the ions are formed with negligible initial velocities right in the region where they are wanted. The oscillating electric field immediately draws them out and takes them on their spiral paths to the periphery. This arrangement is diagrammatically shown in the upper part of Fig. 1.

Fig. 4. External view of apparatus for generation of 1,220,000 volt protons.

The magnetic field. This experimental method requires a highly uniform magnetic field normal to the plane of the accelerating system. For example, if the ions are to circulate around 100 times, thereby gaining energy corresponding to 200 times the applied voltage, it is necessary that the magnetic field be uniform to a fraction of one percent. A general consideration of the matter leads one to the conclusion that, if possible, the magnetic field should be constant to about 0.1 percent from the center outward. Though this presumably

difficult requirement has been met easily by an empirical method of field correction, the magnet used in the present experiments has pole faces machined as accurately as could be done conveniently. Its design was quite similar to that of Curtis.[18] The pole faces were 11 inches in diameter and the gap separation was $1\frac{1}{2}$ inches. Armco iron was used throughout the magnetic circuit. The magnetomotive force was provided by two coils of number 14 double cotton covered wire of 2,000 turns each. No water cooling was incorporated, for the magnet was not intended for high fields. In practice the magnet would give a field of 14,000 gauss for considerable periods without overheating. The pole faces were made parallel to about 0.2 percent and so it was to be expected that the magnetic field produced would be highly uniform. Exploration with a bismuth spiral confirmed this expectation, since it failed to show an appreciable variation of the magnetic field in the region between the poles, excepting within an inch of the periphery.

The collector system. In planning a suitable arrangement for collecting the high speed ions at the periphery of the apparatus, it was clearly desirable to devise something that would collect the high speed ions only and which would also measure their speeds. One might regard it as legitimate to suppose that the magnetic field itself and the distance of the collector from the center of the system would determine the speeds of the ions collected. This would be true provided there were no scattering and reflection of ions. To eliminate these extraneous effects a set of 1 mm slits was arranged on a circle *a* .. *a*, as shown in Fig. 2, of radius about 12 percent greater than the circle, indicated by the dotted line in the figure, having its center at the center of the tube and a radius of 11.5 cm. The two circles were tangent at the first slit as shown. The ions on arrival at the first slit would be traveling presumably on circles approximately like the dotted line, and hence would not be able to pass through the second and third slits to the Faraday collector *C*. Electrostatic deflecting plates *D*, separated by 2 mm, were placed between the first two slits, making possible the application of electrostatic fields to increase the radius of curvature of the paths of the high speed ions sufficiently to allow them to enter the collector. By applying suitable high potentials to the deflecting system in this way, only correspondingly high speed ions were registered.

The collector currents were measured by an electrometer shunted with a suitable high resistance leak.

The oscillator. The high frequency oscillations applied to the electrode were supplied by a 20 kilowatt Federal Telegraph water-cooled power tube in a "tuned plate tuned grid" circuit, for which the diagram of Fig. 2 is self-explanatory.

The Focussing Actions

When one considers the circulation of the ions around many times as they are accelerated to high speeds in this way, one wonders whether in practice an appreciable fraction of those starting out can ever be made to

[18] L. F. Curtis, Jour. Op Soc. Am. 13, 73 (1926).

arrive at the periphery and to pass through a set of slits perhaps 1 mm wide and 1 cm long. The paths of the ions in the course of their acceleration would be several meters, and, because of the unavoidable spreading effects of space charge, thermal velocities and contact electromotive forces, as well as inhomogeneities of the applied fields, it would appear that the effective solid angle of the peripheral slit for the ions starting out would be exceedingly small.

Fortunately, however, this does not turn out to be the case. The electric and magnetic fields have been so arranged that they provide extremely strong focussing actions on the spiraling ions, which keep them circulating close to the median plane of the accelerating system.

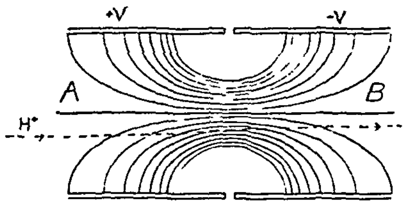


Fig. 5. Diagram indicating the focussing action of the electric field between the accelerating electrodes.

Fig. 5 shows the focussing action of the electric fields. There is depicted a cross-section of the diametral region between the accelerating electrodes with the nature of the field indicated by lines of force. There is shown also a dotted line which represents qualitatively the path of an ion as it passes from the interior of one electrode to the interior of the other. It is seen that, since it is off the median plane in electrode A, on crossing to B it receives an inward displacement towards the median plane. This is because of the existence of the curvature of the field, which over certain regions has an appreciable component normal to the plane, as indicated. If the velocity of the ion is very

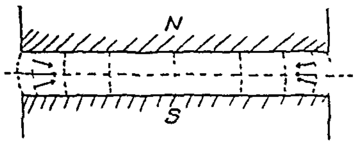


Fig. 6. Diagram indicating focussing action of magnetic field.

high in comparison to the increment of velocity gained in going from plate A to plate B, its displacement towards the center will be relatively small and, to the first approximation, it may be described as due to the ion having been accelerated inward on the first half of its path across and accelerated outward by an equal amount during the remainder of its journey, the net result being a displacement of the ion towards the center without acquiring a net transverse component of velocity. In general, however, the outward acceleration during the second half will not quite compensate the inward acceleration of the first, resulting in a gain of an inward component of velocity as well as an inward displacement. In any event, as the ion spirals around it will migrate back and forth across the median plane and will not be lost to the walls of the tube.

The magnetic field also has a focussing action. Fig. 6 shows diagrammatically the form of the field produced by the magnet. In the central region of the pole faces the magnetic field is quite uniform and normal to the plane of the faces; but out near the periphery the field has a curvature. Ions traveling on circles near the periphery experience thereby magnetic forces, indicated by the arrows. If the circular path is on the median plane then the magnetic force is towards the center in that plane. If the ion is traveling in a circle off the median plane, then there is a component of magnetic force that accelerates it towards the median plane, thereby giving effectively a focussing action.

We have experimentally examined these two focussing actions, using a probe in front of the first slit of the collector system that could be moved up and down across the beam by means of a ground joint (see Fig. 3). It was

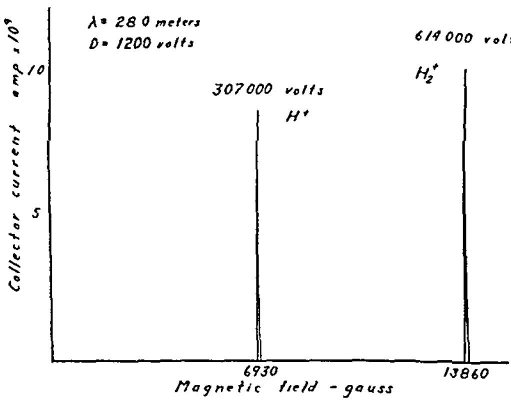


Fig. 7. Ion current to Faraday collector as a function of the magnetic field with oscillations of 28 meters wave-length applied to the accelerating electrodes.

found that the focussing actions were so powerful that *the beam of high speed ions had a width of less than one millimeter.* Such a narrow beam of ions of course is ideal for many experimental studies.

As a further test of the focussing action of the two fields, the median plane of the accelerating system was lowered 3 mm with respect to the plane of symmetry of the magnetic field. It was found that the high speed ion beam at the periphery traveled in a plane that was between the planes of symmetry of the two fields showing that both focussing actions were operative and at the periphery were of the same order of magnitude.

Experimental Results

As a typical example there is shown in Fig. 7 a plot of the ion current to the Faraday collector as a function of the magnetic field for applied oscillations of wave-length 28 meters and with hydrogen in the tube. It is seen that there are only two narrow ranges of magnetic field strength over which ion currents are observed; both correspond exactly to expectations, the one at

6930 gauss involving the resonance of protons, the other, hydrogen molecule ions.

For each wave-length used, *the magnetic field giving the greatest current to the collector agreed precisely with the theoretically expected value.* This is illustrated in Fig. 8 where the curves represent the theoretical hyperbolic relations between wave-length and magnetic field (Eq. 3) for protons and hydrogen molecule ions, and the circles represent the experimental observations. The magnetic fields were measured with a bismuth spiral and the oscillation wave-lengths were determined with a General Radio wavemeter. No effort was made to obtain considerable precision in these measurements, and in consequence their accuracy was hardly greater than 1 percent.

The variation with applied high frequency voltage of the widths of the resonance peaks agreed also with theoretical expectations. It was found that as the voltage was reduced the peaks became sharper, and indeed, with voltages such that the ions were required to spiral around fifty and more times to reach

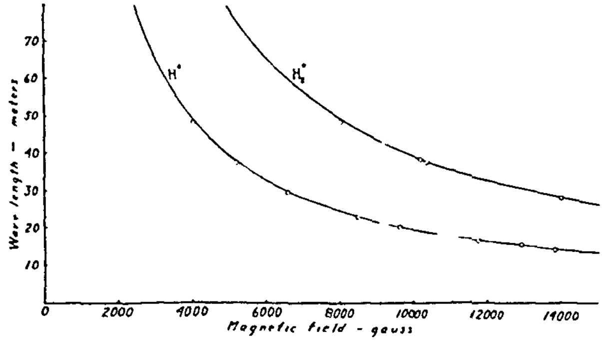


Fig. 8. Magnetic fields producing resonance of ions with oscillations of various wave-lengths: the curves are the theoretical relations (Eq. (3)) for H^+ and H_2^+ ions and the circles are the experimental observations.

the periphery, the ion currents diminished practically to zero when the magnetic field was changed a few tenths of one percent from the optimum value. This sharpness of resonance is understandable when it is remembered that the time required for an ion to execute one of its semi-circular paths is inversely proportional to the magnetic field. If, for example, the magnetic field were one percent greater or less than the resonance value, the ions would find themselves completely out of phase with the oscillations after having made fifty revolutions in the tube. In Fig. 7 the peaks exhibit an appreciable width, and indeed they extend over a one percent range of magnetic field. In most of the experiments, however, the ions circulated around many more times resulting in peaks of such restricted breadth as scarcely to be discernible in a diagram of this sort.

It is of course evident that the upper limit to the number of times the ions will circulate is determined by the degree of uniformity of the average value of the magnetic field along the spiral paths. Indeed, it would seem difficult to construct a magnet with pole faces giving fields of sufficient uniformity to

allow more than 100 accelerations of the ions. But happily there is a very simple empirical way of correcting for the lack of uniformity of the field, that makes possible a surprisingly large voltage amplification. This is accomplished by insertion of thin sheets of iron between the tube and the magnet; either in the central region or out towards the periphery, as may be needed. If the magnetic field is, on the average, slightly less out towards the periphery so that the ions lag in phase more and more with respect to the oscillations as they spiral around, they may be brought back into step again by the insertion near the periphery of a strip of iron of suitable width, thickness and extension. If, on the other hand, the ions tend to get ahead in phase in this region, an effective correction can be made by inserting a suitable iron sheet in the central region.

It should be emphasized in this connection that the requirement is not that the magnetic field has to be uniform everywhere to the extent indicated above; small deviations from uniformity are allowable provided that the average value of the magnetic field over the paths of the ions is such that they traverse successive revolutions in equal intervals of time. Thus, small magnetic field adjustments can be accomplished by increasing or decreasing the field over small portions of successive circular paths of the ions. In the present experiments the most satisfactory adjustment was made by the insertion of a sheet of iron 0.025 cm thick having a shape much like an exclamation point extending radially with the thick end 8 cm wide in the central region and the narrow end 3 cms wide at the periphery. Insertion of this correcting "shim" *increased the amplification factor* (that is, the ratio of the equivalent voltage of the ions arriving at the collector to the maximum high frequency voltage applied to the tube) *from about 75 to about 300.* These figures are of necessity somewhat rough estimates, because no means were conveniently at hand to measure the high frequency voltages applied to the tube. Our estimates are based solely on sparking distances in air, and hence it is not unlikely that the voltage amplifications were even greater.

The greatest voltage amplification was obtained when generating the highest speed ions, 1,220,000 volt-protons. In all our work we have found the experimental method to be increasingly effective in this regard, as in others, as we go to higher voltages.

For example, the optimum pressure of hydrogen in the tube has been found to increase from less than 10^{-4} mm of Hg when generating 200,000 volt-protons to more than 10^{-3} mm when producing 1,000,000 volt-protons. By the optimum pressure is meant the pressure that gives the largest current to the collector for a given electron emission from the filament. The reason for this is, of course, connected with the fact that the effective mean free path of the spiralling particles increases with voltage.

Examples of the observed variation with voltage on the deflecting plates of the ion currents to the collector are shown in Fig. 9. Each curve is for a particular resonance condition; curve *A*, for example, was obtained when protons resonated with 37.5 meter oscillations in a magnetic field of 5180 gauss, thereby theoretically resulting in the arrival of 172,000 volt-protons

at the first slit of the collector system. The wave-lengths used and the theoretically expected equivalent voltages of the ions generated in each instance is indicated in the figure. It is seen that, the higher the equivalent voltage of the ions, the higher was the required deflecting voltage to obtain the maximum ion currents to the collector. Indeed, within the experimental error, the optimum deflecting voltage was proportional to the theoretical kinetic energies of the ions (calculated from Eq. (4)) and was quite independent of the magnitude of the high frequency voltage applied to the accelerating electrode. *These observations constitute incontrovertible evidence that the ions arriving at the collector actually had the high speeds theoretically expected. The observed absolute magnitudes of the deflecting voltages also agreed with theoretical calculations* within the experimental uncertainty of the paths of the ions before entering the deflecting system. Because of the considerable width of the ion source (the filament was 2.5 cm long) the effective center of

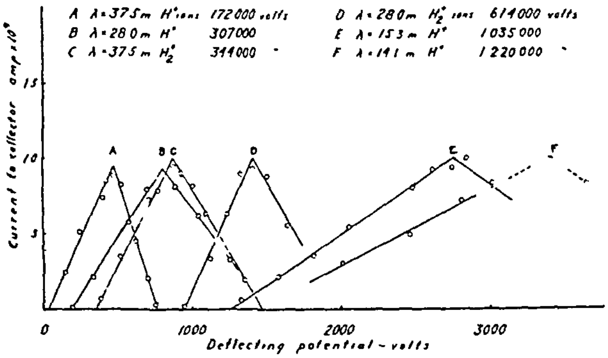


Fig. 9. Ion currents to the Faraday collector as a function of the voltage applied to the deflecting plates. The optimum deflecting voltages are seen to be proportional to the theoretically calculated kinetic energies of the ions (indicated in the figure in volts), thus proving that the ions arriving at the collector actually have the theoretically expected high speeds.

the circular paths of the ions at the periphery was quite broad. This fact together with the slit widths accounted for the absolute range of deflecting voltages over which ion currents reached the collector.

Discussion

The present experiments have accomplished one of the objectives set forth in the introduction, namely, the development of a convenient method for the production of protons having kinetic energies of the order of magnitude of 1,000,000 volt-electrons. It is well to emphasize two particular features that have contributed more than anything else to the effectiveness of the method: the *focussing actions of the electric and magnetic fields*, and the *simple means of empirically correcting the magnetic field* by the introduction of suitable iron strips. The former has solved the practical problem of generation of intense high speed ion beams of restricted cross-section so much desired in studies of collision processes. The latter has eliminated the problem of uniformity of magnetic field, making possible voltage amplifications of more than 300. This in turn has practically eliminated any difficulties associated

with generation and application to the accelerating electrodes of required high frequency voltages. In consequence, we have here a source of high speed light ions that is readily constructed and assembled in a relatively small laboratory space out of quite modest laboratory equipment. The beam of ions so produced has valuable characteristics of convenience and flexibility for many experimental investigations; there are obvious advantages of a steady beam of high speed ions of but one millimeter diameter generated in an apparatus on an ordinary laboratory table. Moreover, the apparatus evolved in the present work is in no respects capricious, but functions always in a satisfactorily predictable fashion. This is illustrated by the fact that the accelerating tube can be taken apart and reassembled, and then within a few hours after re-evacuation steady beams of 1,200,000 protons can always be obtained.

But it is perhaps of even more interest to inquire as to the practical limitations of the method; to see what extensions and developments are foreshadowed by the present experiments.

Of primary importance is the probable experimental limitation on the producible proton energies. The practical limit is set by the size of the electromagnet available; for the final equivalent voltage of the ions at the periphery is proportional to the square of the magnetic field strength and to the square of the radius of the path. For protons, it is not feasible to use magnetic fields much greater than employed in the present work (about 14,000 gauss) because of the difficulties of application of suitably higher frequency oscillations—that is to say, it is not desirable to go much below 14 meters wave-length. However, it is entirely practicable to use a much larger magnet than that employed in the present experiments. At the present time a magnet having pole faces 114 cm in diameter is being installed in our laboratory. As will be seen from Eq. (4), a magnetic field of 14,000 gauss over such a large region *makes possible the production of* 25,000,000 *volt-protons*.

Of course, it may be argued that there are other difficulties which preclude ever reaching such a range of energies. For example, there is the question of whether it is possible to obtain such a great amplification factor that the high frequency voltages necessarily applied to the accelerating electrodes are low enough to be realizable in practice. In the present experiments an amplification of 300 was obtained with no great effort, and it would seem that with more careful correction of the field this amplification could be considerably increased at higher voltages. In the higher range of speeds the variation of mass with velocity begins to be appreciable, but presents no difficulty as it can be allowed for by suitable alteration of the magnetic field in the same empirical manner as is done to correct its otherwise lack of uniformity.

Assuming then a voltage amplification of 500, the production of 25,000,000 volt-protons would require 50,000 volts at a wave-length of 14 meters applied across the accelerators; thus, 25,000 volts on each accelerator with respect to ground. *It does appear entirely feasible to do this*, although to be sure a considerable amount of power would have to be supplied because of the capacity of the system.

Of similar interest is the matter of maximum obtainable beam intensities. In the present experiments no efforts have been made to obtain high intensities and the collector currents have usually been of the order of magnitude of 10^{-9} amp. Using the present method of generation of the ions, there are two factors that can be drawn upon to increase the yield of high speed ions—the electron emission and the pressure of hydrogen in the tube. The electron emission can easily be increased from 10 to 100 times over that used in the present experiments. The effective free paths of the protons increase with voltage so that, as was found to be the case, the maximum usable pressure of hydrogen is governed by the setting in of a high frequency discharge in the tubes due to the voltage on the accelerators. This appears to occur at a pressure greater than 10^{-3} mm of Hg; the reason the critical pressure is so high is probably to be associated with the quenching action of the magnetic field. These considerations make it seem reasonable to expect that, using the present ion source, *high speed ion currents of as much as 0.1 microampere can readily be obtained.*

At all events, it seems that the focussing of the spiralling ions is so effective that a quite considerable portion of those starting out arrive at the collector and that the beam intensity is determined largely by the source. *This method of multiple acceleration is capable of yields of the same order of magnitude as would conceivably result from the direct application of high voltages.*

For a given experimental arrangement the energy of the ions arriving at the collector varies inversely as their masses and directly as their charges. Thus, the large magnet mentioned above makes possible the production of 12,500,000 volt hydrogen molecule ions and doubly charged helium ions (alpha-particles) as well as 25,000,000 volt-protons. Moreover, generating the theoretically maximum value of ion energies becomes much easier with increasing atomic weight because the wave-length of the applied high frequency oscillations increases in a like ratio. For example, using a magnetic field of 14,000 gauss over a region 114 cm in diameter, 2,800,000 volt nitrogen ions could be generated by applying 123 meter oscillations. Broadly speaking, then, the apparatus is well adapted to the production of ions of all the elements up to atomic weight 25 having kinetic energies in excess of 1,000,000 volt-electrons.

We wish to express our gratitude and thanks to the Committee-on-Grants-in-Aid of the National Research Council, the Federal Telegraph Company through the courtesy of Dr. Leonard F. Fuller, Vice-President, the Research Corporation, and the Chemical Foundation for their generous assistance which has made these experiments possible.

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* *By* Professor E. Rutherford, *F.R.S., University of Manchester* *.

§ 1. It is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden † on the scattering of α rays indicate that some of the α particles must suffer a deflexion of more than a right angle at a single encounter. They found, for example, that a small fraction of the incident α particles, about 1 in 20,000, were turned through an average angle of 90° in passing through a layer of gold-foil about ·00004 cm. thick, which was equivalent in stopping-power of the α particle to 1·6 millimetres of air. Geiger ‡ showed later that the most probable angle of deflexion for a pencil of α particles traversing a gold-foil of this thickness was about 0°·87. A simple calculation based on the theory of probability shows that the chance of an α particle being deflected through 90° is vanishingly small. In addition, it will be seen later that the distribution of the α particles for various angles of large deflexion does not follow the probability law to be expected if such large deflexions are made up of a large number of small deviations. It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

Recently Sir J. J. Thomson § has put forward a theory to

* Communicated by the Author. A brief account of this paper was communicated to the Manchester Literary and Philosophical Society in February, 1911.

† Proc. Roy. Soc. lxxxii. p. 495 (1909).

‡ Proc. Roy. Soc. lxxxiii. p. 492 (1910).

§ Camb. Lit. & Phil. Soc. xv. pt. 5 (1910).

explain the scattering of electrified particles in passing through small thicknesses of matter. The atom is supposed to consist of a number N of negatively charged corpuscles, accompanied by an equal quantity of positive electricity uniformly distributed throughout a sphere. The deflexion of a negatively electrified particle in passing through the atom is ascribed to two causes—(1) the repulsion of the corpuscles distributed through the atom, and (2) the attraction of the positive electricity in the atom. The deflexion of the particle in passing through the atom is supposed to be small, while the average deflexion after a large number m of encounters was taken as $\sqrt{m} \cdot \theta$, where θ is the average deflexion due to a single atom. It was shown that the number N of the electrons within the atom could be deduced from observations of the scattering of electrified particles. The accuracy of this theory of compound scattering was examined experimentally by Crowther* in a later paper. His results apparently confirmed the main conclusions of the theory, and he deduced, on the assumption that the positive electricity was continuous, that the number of electrons in an atom was about three times its atomic weight.

The theory of Sir J. J. Thomson is based on the assumption that the scattering due to a single atomic encounter is small, and the particular structure assumed for the atom does not admit of a very large deflexion of an α particle in traversing a single atom, unless it be supposed that the diameter of the sphere of positive electricity is minute compared with the diameter of the sphere of influence of the atom.

Since the α and β particles traverse the atom, it should be possible from a close study of the nature of the deflexion to form some idea of the constitution of the atom to produce the effects observed. In fact, the scattering of high-speed charged particles by the atoms of matter is one of the most promising methods of attack of this problem. The development of the scintillation method of counting single α particles affords unusual advantages of investigation, and the researches of H. Geiger by this method have already added much to our knowledge of the scattering of α rays by matter.

§ 2. We shall first examine theoretically the single encounters † with an atom of simple structure, which is able to

* Crowther, Proc. Roy. Soc. lxxxiv. p. 226 (1910).

† The deviation of a particle throughout a considerable angle from an encounter with a single atom will in this paper be called "single" scattering. The deviation of a particle resulting from a multitude of small deviations will be termed "compound" scattering.

produce large deflexions of an α particle, and then compare the deductions from the theory with the experimental data available.

Consider an atom which contains a charge $\pm Ne$ at its centre surrounded by a sphere of electrification containing a charge $\mp Ne$ supposed uniformly distributed throughout a sphere of radius R. e is the fundamental unit of charge, which in this paper is taken as $4{\cdot}65 \times 10^{-10}$ E.S. unit. We shall suppose that for distances less than 10^{-12} cm. the central charge and also the charge on the α particle may be supposed to be concentrated at a point. It will be shown that the main deductions from the theory are independent of whether the central charge is supposed to be positive or negative. For convenience, the sign will be assumed to be positive. The question of the stability of the atom proposed need not be considered at this stage, for this will obviously depend upon the minute structure of the atom, and on the motion of the constituent charged parts.

In order to form some idea of the forces required to deflect an α particle through a large angle, consider an atom containing a positive charge Ne at its centre, and surrounded by a distribution of negative electricity Ne uniformly distributed within a sphere of radius R. The electric force X and the potential V at a distance r from the centre of an atom for a point inside the atom, are given by

$$X = Ne\left(\frac{1}{r^2} - \frac{r}{R^3}\right)$$

$$V = Ne\left(\frac{1}{r} - \frac{3}{2R} + \frac{r^2}{2R^3}\right).$$

Suppose an α particle of mass m and velocity u and charge E shot directly towards the centre of the atom. It will be brought to rest at a distance b from the centre given by

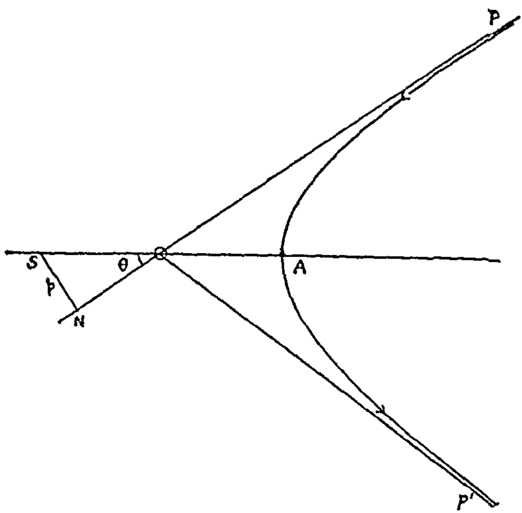
$$\tfrac{1}{2}mu^2 = NeE\left(\frac{1}{b} - \frac{3}{2R} + \frac{b^2}{2R^3}\right).$$

It will be seen that b is an important quantity in later calculations. Assuming that the central charge is $100\,e$, it can be calculated that the value of b for an α particle of velocity $2{\cdot}09 \times 10^9$ cms. per second is about $3{\cdot}4 \times 10^{-12}$ cm. In this calculation b is supposed to be very small compared with R. Since R is supposed to be of the order of the radius of the atom, viz. 10^{-8} cm., it is obvious that the α particle before being turned back penetrates so close to

the central charge, that the field due to the uniform distribution of negative electricity may be neglected. In general, a simple calculation shows that for all deflexions greater than a degree, we may without sensible error suppose the deflexion due to the field of the central charge alone. Possible single deviations due to the negative electricity, if distributed in the form of corpuscles, are not taken into account at this stage of the theory. It will be shown later that its effect is in general small compared with that due to the central field.

Consider the passage of a positive electrified particle close to the centre of an atom. Supposing that the velocity of the particle is not appreciably changed by its passage through the atom, the path of the particle under the influence of a repulsive force varying inversely as the square of the distance will be an hyperbola with the centre of the atom S as the external focus. Suppose the particle to enter the atom in the direction PO (fig. 1), and that the direction of motion

Fig. 1.



on escaping the atom is OP′. OP and OP′ make equal angles with the line SA, where A is the apse of the hyperbola. p=SN=perpendicular distance from centre on direction of initial motion of particle.

Let angle POA $=\theta$.

Let V = velocity of particle on entering the atom, v its velocity at A, then from consideration of angular momentum

$$pV = SA \cdot v.$$

From conservation of energy

$$\tfrac{1}{2}mV^2 = \tfrac{1}{2}mv^2 + \frac{NeE}{SA},$$

$$v^2 = V^2\left(1 - \frac{b}{SA}\right).$$

Since the eccentricity is $\sec\theta$,

$$SA = SO + OA = p\,\mathrm{cosec}\,\theta(1+\cos\theta)$$
$$= p\cot\theta/2,$$
$$p^2 = SA(SA - b) = p\cot\theta/2(p\cot\theta/2 - b),$$
$$\therefore \quad b = 2p\cot\theta.$$

The angle of deviation ϕ of the particle is $\pi - 2\theta$ and

$$\cot\phi/2 = \frac{2p}{b}\text{*} \quad \ldots \ldots \quad (1)$$

This gives the angle of deviation of the particle in terms of b, and the perpendicular distance of the direction of projection from the centre of the atom.

For illustration, the angle of deviation ϕ for different values of p/b are shown in the following table:—

p/b	10	5	2	1	·5	·25	·125
ϕ	5°·7	11°·4	28°	53°	90°	127°	152°

§ 3. *Probability of single deflexion through any angle.*

Suppose a pencil of electrified particles to fall normally on a thin screen of matter of thickness t. With the exception of the few particles which are scattered through a large angle, the particles are supposed to pass nearly normally through the plate with only a small change of velocity. Let n = number of atoms in unit volume of material. Then the number of collisions of the particle with the atom of radius R is $\pi R^2 nt$ in the thickness t.

* A simple consideration shows that the deflexion is unaltered if the forces are attractive instead of repulsive.

The probabilty m of entering an atom within a distance p of its centre is given by

$$m=\pi p^2 nt.$$

Chance dm of striking within radii p and $p+dp$ is given by

$$dm=2\pi pnt\,.\,dp=\frac{\pi}{4}ntb^2\cot\phi/2\,\mathrm{cosec}^2\,\phi/2\,d\phi, \quad . \quad (2)$$

since $$\cot\phi/2=2p/b.$$

The value of dm gives the *fraction* of the total number of particles which are deviated between the angles ϕ and $\phi+d\phi$.

The fraction ρ of the total number of particles which are deflected through an angle greater than ϕ is given by

$$\rho=\frac{\pi}{4}ntb^2\cot^2\phi/2. \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The fraction ρ which is deflected between the angles ϕ_1 and ϕ_2 is given by

$$\rho=\frac{\pi}{4}ntb^2\left(\cot^2\frac{\phi_1}{2}-\cot^2\frac{\phi_2}{2}\right). \quad . \quad . \quad . \quad (4)$$

It is convenient to express the equation (2) in another form for comparison with experiment. In the case of the α rays, the number of scintillations appearing on a *constant* area of a zinc sulphide screen are counted for different angles with the direction of incidence of the particles. Let r = distance from point of incidence of α rays on scattering material, then if Q be the total number of particles falling on the scattering material, the number y of α particles falling on unit area which are deflected through an angle ϕ is given by

$$y=\frac{\mathrm{Q}dm}{2\pi r^2\sin\phi\,.\,d\phi}=\frac{ntb^2\,.\,\mathrm{Q}\,.\,\mathrm{cosec}^4\,\phi/2}{16r^2}. \quad . \quad . \quad (5)$$

Since $b=\dfrac{2\mathrm{N}e\mathrm{E}}{mu^2}$, we see from this equation that the number of α particles (scintillations) per unit area of zinc sulphide screen at a given distance r from the point of

incidence of the rays is proportional to

(1) $\operatorname{cosec}^4 \phi/2$ or $1/\phi^4$ if ϕ be small ;
(2) thickness of scattering material t provided this is small ;
(3) magnitude of central charge Ne ;
(4) and is inversely proportional to $(mu^2)^2$, or to the fourth power of the velocity if m be constant.

In these calculations, it is assumed that the α particles scattered through a large angle suffer only one large deflexion. For this to hold, it is essential that the thickness of the scattering material should be so small that the chance of a second encounter involving another large deflexion is very small. If, for example, the probability of a single deflexion ϕ in passing through a thickness t is 1/1000, the probability of two successive deflexions each of value ϕ is $1/10^6$, and is negligibly small.

The angular distribution of the α particles scattered from a thin metal sheet affords one of the simplest methods of testing the general correctness of this theory of single scattering. This has been done recently for α rays by Dr. Geiger *, who found that the distribution for particles deflected between 30° and 150° from a thin gold-foil was in substantial agreement with the theory. A more detailed account of these and other experiments to test the validity of the theory will be published later.

§ 4. *Alteration of velocity in an atomic encounter.*

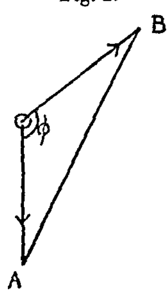
It has so far been assumed that an α or β particle does not suffer an appreciable change of velocity as the result of a single atomic encounter resulting in a large deflexion of the particle. The effect of such an encounter in altering the velocity of the particle can be calculated on certain assumptions. It is supposed that only two systems are involved, viz., the swiftly moving particle and the atom which it traverses supposed initially at rest. It is supposed that the principle of conservation of momentum and of energy applies, and that there is no appreciable loss of energy or momentum by radiation.

* Manch. Lit. & Phil. Soc. 1910.

Let m be mass of the particle,
v_1 = velocity of approach,
v_2 = velocity of recession,
M = mass of atom,
V = velocity communicated to atom as result of encounter.

Let OA (fig. 2) represent in magnitude and direction the momentum mv_1 of the entering particle, and OB the momentum of the receding particle which has been turned through an angle AOB $=\phi$. Then BA represents in magnitude and direction the momentum MV of the recoiling atom.

Fig. 2.



$$(MV)^2=(mv_1)^2+(mv_2)^2-2m^2v_1v_2\cos\phi. \quad (1)$$

By the conservation of energy

$$MV^2=mv_1^2-mv_2^2. \quad . \quad . \quad (2)$$

Suppose $M/m=K$ and $v_2=\rho v_1$, where ρ is <1.

From (1) and (2),

$$(K+1)\rho^2-2\rho\cos\phi=K-1,$$

or $$\rho=\frac{\cos\phi}{K+1}+\frac{1}{K+1}\sqrt{K^2-\sin^2\phi}.$$

Consider the case of an α particle of atomic weight 4, deflected through an angle of 90° by an encounter with an atom of gold of atomic weight 197.

Since $K=49$ nearly,

$$\rho=\sqrt{\frac{K-1}{K+1}}=\cdot 979,$$

or the velocity of the particle is reduced only about 2 per cent. by the encounter.

In the case of aluminium $K=27/4$ and for $\phi=90°$ $\rho=\cdot 86$.

It is seen that the reduction of velocity of the α particle becomes marked on this theory for encounters with the lighter atoms. Since the range of an α particle in air or other matter is approximately proportional to the cube of the velocity, it follows that an α particle of range 7 cms. has its range reduced to 4·5 cms. after incurring a single

deviation of 90° in traversing an aluminium atom. This is of a magnitude to be easily detected experimentally. Since the value of K is very large for an encounter of a β particle with an atom, the reduction of velocity on this formula is very small.

Some very interesting cases of the theory arise in considering the changes of velocity and the distribution of scattered particles when the α particle encounters a light atom, for example a hydrogen or helium atom. A discussion of these and similar cases is reserved until the question has been examined experimentally.

§ 5. *Comparison of single and compound scattering.*

Before comparing the results of theory with experiment, it is desirable to consider the relative importance of single and compound scattering in determining the distribution of the scattered particles. Since the atom is supposed to consist of a central charge surrounded by a uniform distribution of the opposite sign through a sphere of radius R, the chance of encounters with the atom involving small deflexions is very great compared with the chance of a single large deflexion.

This question of compound scattering has been examined by Sir J. J. Thomson in the paper previously discussed (§ 1). In the notation of this paper, the average deflexion ϕ_1 due to the field of the sphere of positive electricity of radius R and quantity Ne was found by him to be

$$\phi_1 = \frac{\pi}{4} \cdot \frac{NeE}{mu^2} \cdot \frac{1}{R}.$$

The average deflexion ϕ_2 due to the N negative corpuscles supposed distributed uniformly throughout the sphere was found to be

$$\phi_2 = \frac{16}{5} \frac{eE}{mu^2} \cdot \frac{1}{R} \sqrt{\frac{3N}{2}}.$$

The mean deflexion due to both positive and negative electricity was taken as

$$(\phi_1^2 + \phi_2^2)^{1/2}.$$

In a similar way, it is not difficult to calculate the average deflexion due to the atom with a central charge discussed in this paper.

Since the radial electric field X at any distance r from the

centre is given by

$$X = Ne\left(\frac{1}{r^2} - \frac{r}{R^3}\right),$$

it is not difficult to show that the deflexion (supposed small) of an electrified particle due to this field is given by

$$\theta = \frac{b}{p}\left(1 - \frac{p^2}{R^2}\right)^{3/2},$$

where p is the perpendicular from the centre on the path of the particle and b has the same value as before. It is seen that the value of θ increases with diminution of p and becomes great for small values of ϕ.

Since we have already seen that the deflexions become very large for a particle passing near the centre of the atom, it is obviously not correct to find the average value by assuming θ is small.

Taking R of the order 10^{-8} cm., the value of p for a large deflexion is for α and β particles of the order 10^{-11} cm. Since the chance of an encounter involving a large deflexion is small compared with the chance of small deflexions, a simple consideration shows that the average small deflexion is practically unaltered if the large deflexions are omitted. This is equivalent to integrating over that part of the cross section of the atom where the deflexions are small and neglecting the small central area. It can in this way be simply shown that the average small deflexion is given by

$$\phi_1 = \frac{3\pi}{8}\frac{b}{R}.$$

This value of ϕ_1 for the atom with a concentrated central charge is three times the magnitude of the average deflexion for the same value of Ne in the type of atom examined by Sir J. J. Thomson. Combining the deflexions due to the electric field and to the corpuscles, the average deflexion is

$$(\phi_1^2 + \phi_2^2)^2 \quad \text{or} \quad \frac{b}{2R}\left(5{\cdot}54 + \frac{15{\cdot}4}{N}\right)^{1/2}.$$

It will be seen later that the value of N is nearly proportional to the atomic weight, and is about 100 for gold. The effect due to scattering of the individual corpuscles expressed by the second term of the equation is consequently small for heavy atoms compared with that due to the distributed electric field.

Neglecting the second term, the average deflexion per atom is $\frac{3\pi b}{8R}$. We are now in a position to consider the relative effects on the distribution of particles due to single and to compound scattering. Following J. J. Thomson's argument, the average deflexion θ_t after passing through a thickness t of matter is proportional to the square root of the number of encounters and is given by

$$\theta_t = \frac{3\pi b}{8R}\sqrt{\pi R^2 . n . t} = \frac{3\pi b}{8}\sqrt{\pi n t},$$

where n as before is equal to the number of atoms per unit volume.

The probability p_1 for compound scattering that the deflexion of the particle is greater than ϕ is equal to $e^{-\phi^2/\theta_t^2}$.

Consequently $$\phi^2 = -\frac{9\pi^3}{64} b^2 nt \log p_1.$$

Next suppose that single scattering alone is operative. We have seen (§ 3) that the probability p_2 of a deflexion greater than ϕ is given by

$$p_2 = \frac{\pi}{4} b^2 . n . t \cot^2 \phi/2.$$

By comparing these two equations

$$p_2 \log p_1 = -\cdot181 \phi^2 \cot^2 \phi/2,$$

ϕ is sufficiently small that

$$\tan \phi/2 = \phi/2,$$

$$p_2 \log p_1 = -\cdot72.$$

If we suppose $p_2 = \cdot5$, then $p_1 = \cdot24$.

If $p_2 = \cdot1$, $p_1 = \cdot0004$.

It is evident from this comparison, that the probability for any given deflexion is always greater for single than for compound scattering. The difference is especially marked when only a small fraction of the particles are scattered through any given angle. It follows from this result that the distribution of particles due to encounters with the atoms is for small thicknesses mainly governed by single scattering. No doubt compound scattering produces some effect in equalizing the distribution of the scattered particles; but its effect becomes relatively smaller, the smaller the fraction of the particles scattered through a given angle.

§ 6. *Comparison of Theory with Experiments.*

On the present theory, the value of the central charge Ne is an important constant, and it is desirable to determine its value for different atoms. This can be most simply done by determining the small fraction of α or β particles of known velocity falling on a thin metal screen, which are scattered between ϕ and $\phi+d\phi$ where ϕ is the angle of deflexion. The influence of compound scattering should be small when this fraction is small.

Experiments in these directions are in progress, but it is desirable at this stage to discuss in the light of the present theory the data already published on scattering of α and β particles.

The following points will be discussed :—

(*a*) The "diffuse reflexion" of α particles, *i. e.* the scattering of α particles through large angles (Geiger and Marsden).

(*b*) The variation of diffuse reflexion with atomic weight of the radiator (Geiger and Marsden).

(*c*) The average scattering of a pencil of α rays transmitted through a thin metal plate (Geiger).

(*d*) The experiments of Crowther on the scattering of β rays of different velocities by various metals.

(*a*) In the paper of Geiger and Marsden (*loc. cit.*) on the diffuse reflexion of α particles falling on various substances it was shown that about 1/8000 of the α particles from radium C falling on a thick plate of platinum are scattered back in the direction of the incidence. This fraction is deduced on the assumption that the α particles are uniformly scattered in all directions, the observations being made for a deflexion of about 90°. The form of experiment is not very suited for accurate calculation, but from the data available it can be shown that the scattering observed is about that to be expected on the theory if the atom of platinum has a central charge of about 100 e.

(*b*) In their experiments on this subject, Geiger and Marsden gave the relative number of α particles diffusely reflected from thick layers of different metals, under similar conditions. The numbers obtained by them are given in the table below, where z represents the relative number of scattered particles, measured by the number of scintillations per minute on a zinc sulphide screen.

Metal.	Atomic weight.	z.	$z/A^{3/2}$.
Lead	207	62	208
Gold	197	67	242
Platinum	195	63	232
Tin	119	34	226
Silver	108	27	241
Copper	64	14·5	225
Iron	56	10·2	250
Aluminium ...	27	3·4	243
		Average	233

On the theory of single scattering, the fraction of the total number of α particles scattered through any given angle in passing through a thickness t is proportional to $n.A^2t$, assuming that the central charge is proportional to the atomic weight A. In the present case, the thickness of matter from which the scattered α particles are able to emerge and affect the zinc sulphide screen depends on the metal. Since Bragg has shown that the stopping power of an atom for an α particle is proportional to the square root of its atomic weight, the value of nt for different elements is proportional to $1/\sqrt{A}$. In this case t represents the greatest depth from which the scattered α particles emerge. The number z of α particles scattered back from a thick layer is consequently proportional to $A^{3/2}$ or $z/A^{3/2}$ should be a constant.

To compare this deduction with experiment, the relative values of the latter quotient are given in the last column. Considering the difficulty of the experiments, the agreement between theory and experiment is reasonably good *.

The single large scattering of α particles will obviously affect to some extent the shape of the Bragg ionization curve for a pencil of α rays. This effect of large scattering should be marked when the α rays have traversed screens of metals of high atomic weight, but should be small for atoms of light atomic weight.

(*c*) Geiger made a careful determination of the scattering of α particles passing through thin metal foils, by the scintillation method, and deduced the most probable angle

* The effect of change of velocity in an atomic encounter is neglected in this calculation.

through which the α particles are deflected in passing through known thicknesses of different kinds of matter.

A narrow pencil of homogeneous α rays was used as a source. After passing through the scattering foil, the total number of α particles deflected through different angles was directly measured. The angle for which the number of scattered particles was a maximum was taken as the most probable angle. The variation of the most probable angle with thickness of matter was determined, but calculation from these data is somewhat complicated by the variation of velocity of the α particles in their passage through the scattering material. A consideration of the curve of distribution of the α particles given in the paper (*loc. cit.* p. 496) shows that the angle through which half the particles are scattered is about 20 per cent greater than the most probable angle.

We have already seen that compound scattering may become important when about half the particles are scattered through a given angle, and it is difficult to disentangle in such cases the relative effects due to the two kinds of scattering. An approximate estimate can be made in the following way:—From (§ 5) the relation between the probabilities p_1 and p_2 for compound and single scattering respectively is given by

$$p_2 \log p_1 = -\cdot 721.$$

The probability q of the combined effects may as a first approximation be taken as

$$q = (p_1^2 + p_2^2)^{1/2}.$$

If $q = \cdot 5$, it follows that

$$p_1 = \cdot 2 \quad \text{and} \quad p_2 = \cdot 46.$$

We have seen that the probability p_2 of a single deflexion greater than ϕ is given by

$$p_2 = \frac{\pi}{4} n \cdot t \cdot b^2 \cot^2 \phi/2.$$

Since in the experiments considered ϕ is comparatively small

$$\frac{\phi\sqrt{p_2}}{\sqrt{\pi n t}} = b = \frac{2NeE}{mu^2}.$$

Geiger found that the most probable angle of scattering of the α rays in passing through a thickness of gold equivalent in stopping power to about ·76 cm. of air was 1° 40′. The angle ϕ through which half the α particles are turned thus corresponds to 2° nearly.

$$t = \cdot 00017 \text{ cm.}; \quad n = 6\cdot 07 \times 10^{22};$$

$$u \text{ (average value)} = 1\cdot 8 \times 10^9.$$

$$E/m = 1\cdot 5 \times 10^{14} \text{ E.S. units}; \quad e = 4\cdot 65 \times 10^{-10}.$$

Taking the probability of single scattering $= \cdot 46$ and substituting the above values in the formula, the value of N for gold comes out to be 97.

For a thickness of gold equivalent in stopping power to 2·12 cms. of air, Geiger found the most probable angle to be 3° 40′. In this case $t = \cdot 00047$, $\phi = 4^{\circ}{\cdot}4$, and average $u = 1{\cdot}7 \times 10^9$, and N comes out to be 114.

Geiger showed that the most probable angle of deflexion for an atom was nearly proportional to its atomic weight. It consequently follows that the value of N for different atoms should be nearly proportional to their atomic weights, at any rate for atomic weights between gold and aluminium.

Since the atomic weight of platinum is nearly equal to that of gold, it follows from these considerations that the magnitude of the diffuse reflexion of α particles through more than 90° from gold and the magnitude of the average small angle scattering of a pencil of rays in passing through gold-foil are both explained on the hypothesis of single scattering by supposing the atom of gold has a central charge of about 100 *e*.

(*d*) *Experiments of Crowther on scattering of β rays.*—We shall now consider how far the experimental results of Crowther on scattering of β particles of different velocities by various materials can be explained on the general theory of single scattering. On this theory, the fraction of β particles p turned through an angle greater than ϕ is given by

$$p = \frac{\pi}{4} n \,.\, t \,.\, b^2 \cot^2 \phi/2.$$

In most of Crowther's experiments ϕ is sufficiently small that $\tan \phi/2$ may be put equal to $\phi/2$ without much error. Consequently

$$\phi^2 = 2\pi\, n \,.\, t \,.\, b^2 \quad \text{if } p = 1/2.$$

On the theory of compound scattering, we have already seen that the chance p_1 that the deflexion of the particles is greater than ϕ is given by

$$\phi^2/\log p_1 = -\frac{9\pi^3}{64} n \,.\, t \,.\, b^2.$$

Since in the experiments of Crowther the thickness t of matter was determined for which $p_1 = 1/2$,

$$\phi^2 = \cdot 96\pi\, n\, t\, b^2.$$

For a probability of 1/2, the theories of single and compound

scattering are thus identical in general form, but differ by a numerical constant. It is thus clear that the main relations on the theory of compound scattering of Sir J. J. Thomson, which were verified experimentally by Crowther, hold equally well on the theory of single scattering.

For example, if t_m be the thickness for which half the particles are scattered through an angle ϕ, Crowther showed that $\phi/\sqrt{t_m}$ and also $\frac{mu^2}{E}\cdot\sqrt{t_m}$ were constants for a given material when ϕ was fixed. These relations hold also on the theory of single scattering. Notwithstanding this apparent similarity in form, the two theories are fundamentally different. In one case, the effects observed are due to cumulative effects of small deflexions, while in the other the large deflexions are supposed to result from a single encounter. The distribution of scattered particles is entirely different on the two theories when the probability of deflexion greater than ϕ is small.

We have already seen that the distribution of scattered α particles at various angles has been found by Geiger to be in substantial agreement with the theory of single scattering, but cannot be explained on the theory of compound scattering alone. Since there is every reason to believe that the laws of scattering of α and β particles are very similar, the law of distribution of scattered β particles should be the same as for α particles for small thicknesses of matter. Since the value of mu^2/E for the β particles is in most cases much smaller than the corresponding value for the α particles, the chance of large single deflexions for β particles in passing through a given thickness of matter is much greater than for α particles. Since on the theory of single scattering the fraction of the number of particles which are deflected through a given angle is proportional to kt, where t is the thickness supposed small and k a constant, the number of particles which are undeflected through this angle is proportional to $1-kt$. From considerations based on the theory of compound scattering, Sir J. J. Thomson deduced that the probability of deflexion less than ϕ is proportional to $1-e^{-\mu/t}$ where μ is a constant for any given value of ϕ.

The correctness of this latter formula was tested by Crowther by measuring electrically the fraction I/I_0 of the scattered β particles which passed through a circular opening subtending an angle of 36° with the scattering material. If

$$I/I_0=1-e^{-\mu/t},$$

the value of I should decrease very slowly at first with

increase of t. Crowther, using aluminium as scattering material, states that the variation of I/I_0 was in good accord with this theory for small values of t. On the other hand, if single scattering be present, as it undoubtedly is for α rays, the curve showing the relation between I/I_0 and t should be nearly linear in the initial stages. The experiments of Madsen * on scattering of β rays, although not made with quite so small a thickness of aluminium as that used by Crowther, certainly support such a conclusion. Considering the importance of the point at issue, further experiments on this question are desirable.

From the table given by Crowther of the value $\phi/\sqrt{t_m}$ for different elements for β rays of velocity $2{\cdot}68 \times 10^{10}$ cms. per second, the values of the central charge Ne can be calculated on the theory of single scattering. It is supposed, as in the case of the α rays, that for the given value of $\phi/\sqrt{t_m}$ the fraction of the β particles deflected by single scattering through an angle greater than ϕ is ·46 instead of ·5.

The values of N calculated from Crowther's data are given below.

Element.	Atomic weight.	$\phi/\sqrt{t_m}$.	N.
Aluminium	27	4·25	22
Copper	63·2	10·0	42
Silver	108	15·4	78
Platinum	194	29·0	138

It will be remembered that the values of N for gold deduced from scattering of the α rays were in two calculations 97 and 114. These numbers are somewhat smaller than the values given above for platinum (viz. 138), whose atomic weight is not very different from gold. Taking into account the uncertainties involved in the calculation from the experimental data, the agreement is sufficiently close to indicate that the same general laws of scattering hold for the α and β particles, notwithstanding the wide differences in the relative velocity and mass of these particles.

As in the case of the α rays, the value of N should be most simply determined for any given element by measuring

* Phil. Mag. xviii. p. 909 (1909).

the small fraction of the incident β particles scattered through a large angle. In this way, possible errors due to small scattering will be avoided.

The scattering data for the β rays, as well as for the α rays, indicate that the central charge in an atom is approximately proportional to its atomic weight. This falls in with the experimental deductions of Schmidt*. In his theory of absorption of β rays, he supposed that in traversing a thin sheet of matter, a small fraction α of the particles are stopped, and a small fraction β are reflected or scattered back in the direction of incidence. From comparison of the absorption curves of different elements, he deduced that the value of the constant β for different elements is proportional to nA^2 where n is the number of atoms per unit volume and A the atomic weight of the element. This is exactly the relation to be expected on the theory of single scattering if the central charge on an atom is proportional to its atomic weight.

§ 7. *General Considerations.*

In comparing the theory outlined in this paper with the experimental results, it has been supposed that the atom consists of a central charge supposed concentrated at a point, and that the large single deflexions of the α and β particles are mainly due to their passage through the strong central field. The effect of the equal and opposite compensating charge supposed distributed uniformly throughout a sphere has been neglected. Some of the evidence in support of these assumptions will now be briefly considered. For concreteness, consider the passage of a high speed α particle through an atom having a positive central charge Ne, and surrounded by a compensating charge of N electrons. Remembering that the mass, momentum, and kinetic energy of the α particle are very large compared with the corresponding values for an electron in rapid motion, it does not seem possible from dynamic considerations that an α particle can be deflected through a large angle by a close approach to an electron, even if the latter be in rapid motion and constrained by strong electrical forces. It seems reasonable to suppose that the chance of single deflexions through a large angle due to this cause, if not zero, must be exceedingly small compared with that due to the central charge.

It is of interest to examine how far the experimental evidence throws light on the question of the extent of the

* *Annal. d. Phys.* iv. 23. p. 671 (1907).

distribution of the central charge. Suppose, for example, the central charge to be composed of N unit charges distributed over such a volume that the large single deflexions are mainly due to the constituent charges and not to the external field produced by the distribution. It has been shown (§ 3) that the fraction of the α particles scattered through a large angle is proportional to $(NeE)^2$, where Ne is the central charge concentrated at a point and E the charge on the deflected particle. If, however, this charge is distributed in single units, the fraction of the α particles scattered through a given angle is proportional to Ne^2 instead of N^2e^2. In this calculation, the influence of mass of the constituent particle has been neglected, and account has only been taken of its electric field. Since it has been shown that the value of the central point charge for gold must be about 100, the value of the distributed charge required to produce the same proportion of single deflexions through a large angle should be at least 10,000. Under these conditions the mass of the constituent particle would be small compared with that of the α particle, and the difficulty arises of the production of large single deflexions at all. In addition, with such a large distributed charge, the effect of compound scattering is relatively more important than that of single scattering. For example, the probable small angle of deflexion of a pencil of α particles passing through a thin gold foil would be much greater than that experimentally observed by Geiger (§ *b*–*c*). The large and small angle scattering could not then be explained by the assumption of a central charge of the same value. Considering the evidence as a whole, it seems simplest to suppose that the atom contains a central charge distributed through a very small volume, and that the large single deflexions are due to the central charge as a whole, and not to its constituents. At the same time, the experimental evidence is not precise enough to negative the possibility that a small fraction of the positive charge may be carried by satellites extending some distance from the centre. Evidence on this point could be obtained by examining whether the same central charge is required to explain the large single deflexions of α and β particles; for the α particle must approach much closer to the centre of the atom than the β particle of average speed to suffer the same large deflexion.

The general data available indicate that the value of this central charge for different atoms is approximately proportional to their atomic weights, at any rate for atoms heavier than aluminium. It will be of great interest to examine

experimentally whether such a simple relation holds also for the lighter atoms. In cases where the mass of the deflecting atom (for example, hydrogen, helium, lithium) is not very different from that of the α particle, the general theory of single scattering will require modification, for it is necessary to take into account the movements of the atom itself (see § 4).

It is of interest to note that Nagaoka * has mathematically considered the properties of a "Saturnian" atom which he supposed to consist of a central attracting mass surrounded by rings of rotating electrons. He showed that such a system was stable if the attractive force was large. From the point of view considered in this paper, the chance of large deflexion would practically be unaltered, whether the atom is considered to be a disk or a sphere. It may be remarked that the approximate value found for the central charge of the atom of gold ($100\,e$) is about that to be expected if the atom of gold consisted of 49 atoms of helium, each carrying a charge $2\,e$. This may be only a coincidence, but it is certainly suggestive in view of the expulsion of helium atoms carrying two unit charges from radioactive matter.

The deductions from the theory so far considered are independent of the sign of the central charge, and it has not so far been found possible to obtain definite evidence to determine whether it be positive or negative. It may be possible to settle the question of sign by consideration of the difference of the laws of absorption of the β particle to be expected on the two hypotheses, for the effect of radiation in reducing the velocity of the β particle should be far more marked with a positive than with a negative centre. If the central charge be positive, it is easily seen that a positively charged mass if released from the centre of a heavy atom, would acquire a great velocity in moving through the electric field. It may be possible in this way to account for the high velocity of expulsion of α particles without supposing that they are initially in rapid motion within the atom.

Further consideration of the application of this theory to these and other questions will be reserved for a later paper, when the main deductions of the theory have been tested experimentally. Experiments in this direction are already in progress by Geiger and Marsden.

University of Manchester,
April 1911.

* Nagaoka, Phil. Mag. vii. p. 445 (1904).

LIV. *Collision of α Particles with Light Atoms.* IV. *An Anomalous Effect in Nitrogen.* *By* Professor Sir E. RUTHERFORD, *F.R.S.**

IT has been shown in paper I. that a metal source, coated with a deposit of radium C, always gives rise to a number of scintillations on a zinc sulphide screen far beyond the range of the α particles. The swift atoms causing these scintillations carry a positive charge and are deflected by a magnetic field, and have about the same range and energy as the swift H atoms produced by the passage of α particles through hydrogen. These "natural" scintillations are believed to be due mainly to swift H atoms from the radioactive source, but it is difficult to decide whether they are expelled from the radioactive source itself or are due to the action of α particles on occluded hydrogen.

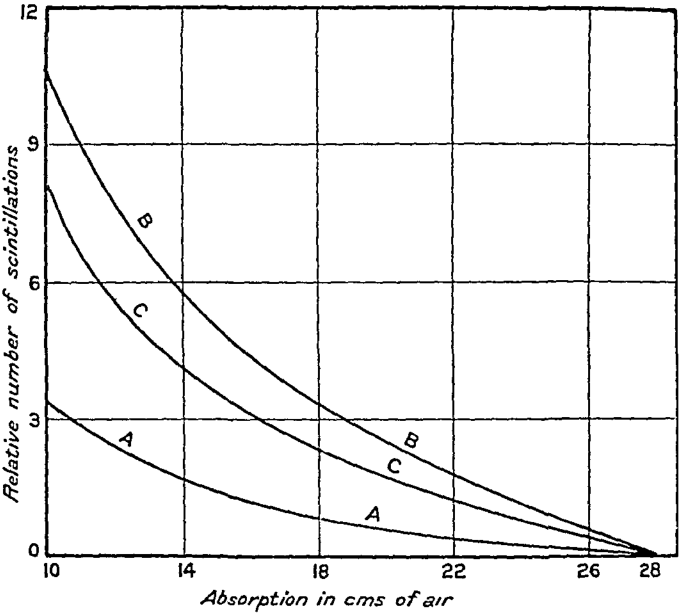
The apparatus employed to study these "natural" scintillations is the same as that described in paper I. The intense source of radium C was placed inside a metal box about 3 cm. from the end, and an opening in the end of the box was covered with a silver plate of stopping power equal to about 6 cm. of air. The zinc sulphide screen was mounted outside, about 1 mm. distant from the silver plate, to admit of the introduction of absorbing foils between them. The whole apparatus was placed in a strong magnetic field to deflect the β rays. The variation in the number of these "natural" scintillations with absorption in terms of cms. of air is shown in fig. 1, curve A. In this case, the air in the box was exhausted and absorbing foils of aluminium were used. When dried oxygen or carbon dioxide was admitted into the vessel, the number of scintillations diminished to about the amount to be expected from the stopping power of the column of gas.

A surprising effect was noticed, however, when dried air was introduced. Instead of diminishing, the number of scintillations was increased, and for an absorption corresponding to about 19 cm. of air the number was about twice that observed when the air was exhausted. It was clear from this experiment that the α particles in their passage through air gave rise to long-range scintillations which appeared to the eye to be about equal in brightness to H scintillations. A systematic series of observations was undertaken to account for the origin of these scintillations. In the first place we have seen that the passage of α particles through nitrogen and

* Communicated by the Author.

oxygen gives rise to numerous bright scintillations which have a range of about 9 cm. in air. These scintillations have about the range to be expected if they are due to swift N or O atoms, carrying unit charge, produced by collision with α particles.

Fig 1.



All experiments have consequently been made with an absorption greater than 9 cm. of air, so that these atoms are completely stopped before reaching the zinc sulphide screen.

It was found that these long-range scintillations could not be due to the presence of water vapour in the air; for the number was only slightly reduced by thoroughly drying the air. This is to be expected, since on the average the number of the additional scintillations due to air was equivalent to the number of H atoms produced by the mixture of hydrogen at 6 cm. pressure with oxygen. Since on the average the vapour pressure of water in air was not more than 1 cm., the effects of complete drying would not reduce the number by more than one sixth. Even when oxygen and carbon dioxide saturated with water vapour at 20° C.

were introduced in place of dry air, the number of scintillations was much less than with dry air.

It is well known that the amount of hydrogen or gases containing hydrogen is normally very small in atmospheric air. No difference was observed whether the air was taken directly from the room or from outside the laboratory or was stored for some days over water.

There was the possibility that the effect in air might be due to liberation of H atoms from the dust nuclei in the air. No appreciable difference, however, was observed when the dried air was filtered through long plugs of cotton-wool, or by storage over water for some days to remove dust nuclei.

Since the anomalous effect was observed in air, but not in oxygen, or carbon dioxide, it must be due either to nitrogen or to one of the other gases present in atmospheric air. The latter possibility was excluded by comparing the effects produced in air and in chemically prepared nitrogen. The nitrogen was obtained by the well-known method of adding ammonium chloride to sodium nitrite, and stored over water. It was carefully dried before admission to the apparatus. With pure nitrogen, the number of long-range scintillations under similar conditions was greater than in air. As a result of careful experiments, the ratio was found to be 1·25, the value to be expected if the scintillations are due to nitrogen.

The results so far obtained show that the long-range scintillations obtained from air must be ascribed to nitrogen, but it is important, in addition, to show that they are due to collision of α particles with atoms of nitrogen through the volume of the gas. In the first place, it was found that the number of the scintillations varied with the pressure of the air in the way to be expected if they resulted from collision of α particles along the column of gas. In addition, when an absorbing screen of gold or aluminium was placed close to the source, the range of the scintillations was found to be reduced by the amount to be expected if the range of the expelled atom was proportional to the range of the colliding α particles. These results show that the scintillations arise from the volume of the gas and are not due to some surface effect in the radioactive source.

In fig. 1 curve A the results of a typical experiment are given showing the variation in the number of natural scintillations with the amount of absorbing matter in their path measured in terms of centimetres of air for α particles. In these experiments carbon dioxide was introduced at a pressure calculated to give the same absorption of the α rays as ordinary air. In curve B the corresponding curve is given when air

at N.T.P. is introduced in place of carbon dioxide. The difference curve C shows the corresponding variation of the number of scintillations arising from the nitrogen in the air. It was generally observed that the ratio of the nitrogen effect to the natural effect was somewhat greater for 19 cm. than for 12 cm. absorption.

In order to estimate the magnitude of the effect, the space between the source and screen was filled with carbon dioxide at diminished pressure and a known pressure of hydrogen was added. The pressure of the carbon dioxide and of hydrogen were adjusted so that the total absorption of α particles in the mixed gas should be equal to that of the air. In this way it was found that the curve of absorption of H atoms produced under these conditions was somewhat steeper than curve C of fig. 1. As a consequence, the amount of hydrogen mixed with carbon dioxide required to produce a number of scintillations equal to that of air, increased with the increase of absorption. For example, the effect in air was equal to about 4 cm. of hydrogen at 12 cm. absorption, and about 8 cm. at 19 cm. absorption. For a mean value of the absorption, the effect was equal to about 6 cm. of hydrogen. This increased absorption of H atoms under similar conditions indicated either that (1) the swift atoms from air had a somewhat greater range than the H atoms, or (2) that the atoms from air were projected more in the line of flight of the α particles.

While the maximum range of the scintillations from air using radium C as a source of α rays appeared to be about the same, viz. 28 cm., as for H atoms produced from hydrogen, it was difficult to fix the end of the range with certainty on account of the smallness of the number and the weakness of the scintillations. Some special experiments were made to test whether, under favourable conditions, any scintillations due to nitrogen could be observed beyond 28 cm. of air absorption. For this purpose a strong source (about 60 mg. Ra activity) was brought within 2·5 cm. of the zinc sulphide screen, the space between containing dry air. On still further reducing the distance, the screen became too bright to detect very feeble scintillations. No certain evidence of scintillations was found beyond a range of 28 cm. It would therefore appear that (2) above is the more probable explanation.

In a previous paper (III.) we have seen that the number of swift atoms of nitrogen or oxygen produced per unit path by collision with α particles is about the same as the corresponding number of H atoms in hydrogen. Since the number of long-range scintillations in air is equivalent to that produced under similar conditions in a column of hydrogen at 6 cm.

pressure, we may consequently conclude that only one long-range atom is produced for every 12 close collisions giving rise to a swift nitrogen atom of maximum range 9 cm

It is of interest to give data showing the number of long-range scintillations produced in nitrogen at atmospheric pressure under definite conditions. For a column of nitrogen 3·3 cm. long, and for a total absorption of 19 cm. of air from the source, the number due to nitrogen per milligram of activity is ·6 per minute on a screen of 3·14 sq. mm. area.

Both as regards range and brightness of scintillations, the long-range atoms from nitrogen closely resemble H atoms, and in all probability are hydrogen atoms. In order, however, to settle this important point definitely, it is necessary to determine the deflexion of these atoms in a magnetic field. Some preliminary experiments have been made by a method similar to that employed in measuring the velocity of the H atom (see paper II.). The main difficulty is to obtain a sufficiently large deflexion of the stream of atoms and yet have a sufficient number of scintillations per minute for counting. The α rays from a strong source passed through dry air between two parallel horizontal plates 3 cm. long and 1·6 mm. apart, and the number of scintillations on the screen placed near the end of the plates was observed for different strengths of the magnetic field. Under these conditions, when the scintillations arise from the whole length of the column of air between the plates, the strongest magnetic field available reduced the number of scintillations by only 30 per cent. When the air was replaced by a mixture of carbon dioxide and hydrogen of the same stopping power for α rays, about an equal reduction was noted. As far as the experiment goes, this is an indication that the scintillations are due to H atoms; but the actual number of scintillations and the amount of reduction was too small to place much reliance on the result. In order to settle this question definitely, it will probably prove necessary to employ a solid nitrogen compound, free from hydrogen, as a source, and to use much stronger sources of α rays. In such experiments, it will be of importance to discriminate between the deflexions due to H atoms and possible atoms of atomic weight 2. From the calculations given in paper III., it is seen that a collision of an α particle with a free atom of mass 2 should give rise to an atom of range about 32 cm. in air, and of initial energy about ·89 of that of the H atom produced under similar conditions. The deflexion of the pencil of these rays in a magnetic field should be about ·6 of that shown by a corresponding pencil of H atoms.

Discussion of results.

From the results so far obtained it is difficult to avoid the conclusion that the long-range atoms arising from collision of α particles with nitrogen are not nitrogen atoms but probably atoms of hydrogen, or atoms of mass 2. If this be the case, we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus. We have drawn attention in paper III. to the rather surprising observation that the range of the nitrogen atoms in air is about the same as the oxygen atoms, although we should expect a difference of about 19 per cent. If in collisions which give rise to swift nitrogen atoms, the hydrogen is at the same time disrupted, such a difference might be accounted for, for the energy is then shared between two systems.

It is of interest to note, that while the majority of the light atoms, as is well known, have atomic weights represented by $4n$ or $4n+3$ where n is a whole number, nitrogen is the only atom which is expressed by $4n+2$. We should anticipate from radioactive data that the nitrogen nucleus consists of three helium nuclei each of atomic mass 4 and either two hydrogen nuclei or one of mass 2. If the H nuclei were outriders of the main system of mass 12, the number of close collisions with the bound H nuclei would be less than if the latter were free, for the α particle in a collision comes under the combined field of the H nucleus and of the central mass. Under such conditions, it is to be expected that the α particle would only occasionally approach close enough to the H nucleus to give it the maximum velocity, although in many cases it may give it sufficient energy to break its bond with the central mass. Such a point of view would explain why the number of swift H atoms from nitrogen is less than the corresponding number in free hydrogen and less also than the number of swift nitrogen atoms. The general results indicate that the H nuclei, which are released, are distant about twice the diameter of the electron (7×10^{-13} cm.) from the centre of the main atom. Without a knowledge of the laws of force at such small distances, it is difficult to estimate the energy required to free the H nucleus or to calculate the maximum velocity that can be given to the escaping H atom. It is not to be expected, *a priori*, that the velocity or range of the H atom released from the nitrogen atom should be identical with that due to a collision in free hydrogen.

Taking into account the great energy of motion of the α particle expelled from radium C, the close collision of such

an α particle with a light atom seems to be the most likely agency to promote the disruption of the latter ; for the forces on the nuclei arising from such collisions appear to be greater than can be produced by any other agency at present available. Considering the enormous intensity of the forces brought into play, it is not so much a matter of surprise that the nitrogen atom should suffer disintegration as that the α particle itself escapes disruption into its constituents. The results as a whole suggest that, if α particles—or similar projectiles—of still greater energy were available for experiment, we might expect to break down the nucleus structure of many of the lighter atoms.

I desire to express my thanks to Mr. William Kay for his invaluable assistance in counting scintillations.

University of Manchester,
April 1919.

LV. *The Rotational Oscillation of a Cylinder in a Viscous Liquid.* *By* D. Coster *.

THIS problem has been dealt with by Stokes † for the purpose of numerical calculations to determine the viscosity of the air. Still, I think it interesting to publish another solution of the problem which gives more opportunity of discussing the different cases, though it is perhaps less adapted to precise calculations.

The method to be followed will be in the main the same as that used by Prof. Verschaffelt in the analogous case of the sphere ‡. We consider the rotational swings about its axis of an infinitely long cylinder which executes a forced vibration. Our object will be to ascertain the motion in the liquid which will establish itself after an infinite time (in practice after a relatively short time §) in order to compute the frictional moment of forces exerted on the cylinder by the liquid. The calculations will be referred to a height of 1 cm.

The motion of the cylinder may be represented by $\alpha = a \cos pt$ where α is the angle of rotation. An obvious assumption to be made is that the liquid will be set in motion in coaxial cylindrical shells each of which will execute its oscillations as a whole. On this assumption it is not difficult

* Communicated by Prof. G. N. Watson, M.A., D.Sc. First published in the Amsterdam Proc. May 1918, vol. xxi. p. 193.

† Math. Papers, vol. v. p. 207.

‡ *Cf.* Amst. Proc. vol. xviii. p. 840; Comm. Leiden, 148 C.

§ *Cf.* Comm. Leiden, p. 22, footnote.

On the Interaction of Elementary Particles. I.

By Hideki YUKAWA.

(Read Nov 17, 1934)

§ 1. Introduction

At the present stage of the quantum theory little is known about the nature of interaction of elementary particles. Heisenberg considered the interaction of "Platzwechsel" between the neutron and the proton to be of importance to the nuclear structure.(1)

Recently Fermi treated the problem of β-disintegration on the hypothesis of "neutrino"(2). According to this theory, the neutron and the proton can interact by emitting and absorbing a pair of neutrino and electron. Unfortunately the interaction energy calculated on such assumption is much too small to account for the binding energies of neutrons and protons in the nucleus.(3)

To remove this defect, it seems natural to modify the theory of Heisenberg and Fermi in the following way. The transition of a heavy particle from neutron state to proton state is not always accompanied by the emission of light particles, i. e., a neutrino and an electron, but the energy liberated by the transition is taken up sometimes by another heavy particle, which in turn will be transformed from proton state into neutron state. If the probability of occurrence of the latter process is much larger than that of the former, the interaction between the neutron and the proton will be much larger than in the case of Fermi, whereas the probability of emission of light particles is not affected essentially.

Now such interaction between the elementary particles can be described by means of a field of force, just as the interaction between the charged particles is described by the electromagnetic field. The above considerations show that the interaction of heavy particles with this field is much larger than that of light particles with it.

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(1) W. Heisenberg, Zeit f. Phys 77, 1 (1932); 78, 156 (1932); 80, 587 (1933) We shall denote the first of them by I

(2) E Fermi, ibid. 88, 161 (1394)

(3) Ig. Tamm, Nature 133, 981 (1934); D. Iwanenko, ibid 981 (1934).

In the quantum theory this field should be accompanied by a new sort of quantum, just as the electromagnetic field is accompanied by the photon.

In this paper the possible natures of this field and the quantum accompanying it will be discussed briefly and also their bearing on the nuclear structure will be considered.

Besides such an exchange force and the oridinary electric and magnetic forces there may be other forces between the elementary particles, but we disregard the latter for the moment.

Fuller account will be made in the next paper.

§ 2. Field describing the interaction

In analogy with the scalar potential of the electromagnetic field, a function $U(x, y, z, t)$ is introduced to describe the field between the neutron and the proton. This function will satisfy an equation similar to the wave equation for the electromagnetic potential.

Now the eqnation

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right\} U = 0 \tag{1}$$

has only static solution with central symmetry $\frac{1}{r}$, except the additive and the multiplicative constants. The potential of force between the neutron and the proton should, however, not be of Coulomb type, but decrease more rapidly with distance. It can be expressed, for example, by

$$+ \text{ or } -g^2\frac{e^{-\lambda r}}{r}, \tag{2}$$

where g is a constant with the dimension of electric charge, i.e., cm.$^{\frac{3}{2}}$ sec.$^{-1}$ gr.$^{\frac{1}{2}}$ and λ with the dimention cm.$^{-1}$

Since this function is a static solution with central symmetry of the wave equation

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \lambda^2\right\} U = 0, \tag{3}$$

let this equation be assumed to be the correct equation for U in vacuum. In the presence of the heavy particles, the U-field interacts with them and causes the transition from neutron state to proton state.

Now, if we introduce the matrices[4]

$$\tau_1=\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix},\quad \tau_2=\begin{pmatrix}0 & -i\\ i & 0\end{pmatrix},\quad \tau_3=\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$

and denote the neutron state and the proton state by $\tau_3=1$ and $\tau_3=-1$ respectively, the wave equation is given by

$$\left\{\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\lambda^2\right\}U=-4\pi g\,\tilde{\Psi}\frac{\tau_1-i\tau_2}{2}\Psi, \tag{4}$$

where Ψ denotes the wave function of the heavy particles, being a function of time, position, spin as well as τ_3', which takes the value either 1 or -1.

Next, the conjugate complex function $\tilde{U}(x,y,z,t)$, satisfying the equation

$$\left\{\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\lambda^2\right\}\tilde{U}=-4\pi g\,\tilde{\Psi}\frac{\tau_1+i\tau_2}{2}\Psi, \tag{5}$$

is introduced, corresponding to the inverse transition from proton to neutron state.

Similar equation will hold for the vector function, which is the analogue of the vector potential of the electromagnetic field. However, we disregard it for the moment, as there's no correct relativistic theory for the heavv particles. Hence simple non-relativistic wave equation neglecting spin will be used for the heavy particle, in the following way

$$\left\{\frac{h^2}{4}\left(\frac{1+\tau_3}{M_N}+\frac{1-\tau_3}{M_P}\right)\Delta+ih\frac{\partial}{\partial t}-\frac{1+\tau_3}{2}M_Nc^2-\frac{1-\tau_3}{2}M_Pc^2 -g\left(\tilde{U}\frac{\tau_1-i\tau_2}{2}+U\frac{\tau_1+i\tau_2}{2}\right)\right\}\Psi=0, \tag{6}$$

where h is Planck's constant divided by 2π and M_N, M_P are the masses of the neutron and the proton respectively. The reason for taking the negative sign in front of g will be mentioned later.

The equation (6) corresponds to the Hamiltonian

$$H=\left(\frac{1+\tau_3}{4M_N}+\frac{1-\tau_3}{4M_P}\right)p^2+\frac{1+\tau_3}{2}M_Nc^2+\frac{1-\tau_3}{2}M_Pc^2 +g\left(\tilde{U}\frac{\tau_1-i\tau_2}{2}+U\frac{\tau_1+i\tau_2}{2}\right) \tag{7}$$

(4) Heisenberg, loc, cit. I.

where p is the momentum of the particle. If we put $M_N c^2 - M_P c^2 = D$ and $M_N + M_P = 2M$, the equation (7) becomes approximately

$$H = \frac{p^2}{2M} + \frac{g}{2}\{\tilde{U}(\tau_1 - i\tau_2) + U(\tau_1 + i\tau_2)\} + \frac{D}{2}\tau_3, \tag{8}$$

where the constant term Mc^2 is omitted.

Now consider two heavy particles at points (x_1, y_1, z_1) and (x_2, y_2, z_2) respectively and assume their relative velocity to be small. The fields at (x_1, y_1, z_1) due to the particle at $(x_2 y_2, z_2)$ are, from (4) and (5),

$$\left.\begin{aligned} U(x_1, y_1, z_1) &= g\frac{e^{-\lambda r_{12}}}{r_{12}}\frac{(\tau_1^{(2)} - i\tau_2^{(2)})}{2} \\ \text{and} \qquad & \\ \tilde{U}(x, y_1, z_1) &= g\frac{e^{-\lambda r_{12}}}{r_{12}}\frac{(\tau_1^{(2)} + i\tau_2^{(2)})}{2}, \end{aligned}\right\} \tag{9}$$

where $(\tau_1^{(1)}, \tau_2^{(1)}, \tau_3^{(1)})$ and $(\tau_1^{(2)}, \tau_2^{(2)}, \tau_3^{(2)})$ are the matrices relating to the first and the second particles respectively, and r_{12} is the distance between them.

Hence the Hamiltonian for the system is given, in the absence of the external fields, by

$$\begin{aligned} H = \frac{p_1^2}{2M} + \frac{p_2^2}{2M} + \frac{g^2}{4}\{(\tau_1^{(1)} - i\tau_2^{(1)})(\tau_1^{(2)} + i\tau_2^{(2)}). \\ + (\tau_1^{(1)} + i\tau_2^{(1)})(\tau_1^{(2)} - i\tau_2^{(2)})\}\frac{e^{-\lambda r_{12}}}{r_{12}} + (\tau_3^{(1)} + \tau_3^{(2)})D \\ = \frac{p_1^2}{2M} + \frac{p_2^2}{2M} + \frac{g^2}{2}(\tau_1^{(1)}\tau_1^{(2)} + \tau_2^{(1)}\tau_2^{(2)})\frac{e^{-\lambda r_{12}}}{r_{12}} + (\tau_3^{(1)} + \tau_3^{(2)})D, \end{aligned} \tag{10}$$

where p_1, p_2 are the momenta of the particles.

This Hamiltonian is equivalent to Heisenberg's Hamiltonian (1),[5] if we take for " Platzwechselintegral "

$$J(r) = -g^2\frac{e^{-\lambda r}}{r}, \tag{11}$$

except that the interaction between the neutrons and the electrostatic repulsion between the protons are not taken into account. Heisenberg took the positive sign for $J(r)$, so that the spin of the lowest energy state of H^2 was O, whereas in our case, owing to the negative sign in front of g^2, the lowest energy state has the spin 1, which is required

(5) Heisenberg, I.

from the experiment.

Two constants g and λ appearing in the above equations should be determined by comparison with experiment. For example, using the Hamiltonian (10) for heavy particles, we can calculate the mass defect of H^2 and the probability of scattering of a neutron by a proton provided that the relative velocity is small compared with the light velocity.[6]

Rough estimation shows that the calculated values agree with the experimental results, if we take for λ the value between $10^{12}\mathrm{cm}^{-1}$. and $10^{13}\mathrm{cm}^{-1}$. and for g a few times of the elementary charge e, although no direct relation between g and e was suggested in the above considerations.

§ 3. Nature of the quanta accompanying the field

The U-field above considered should be quantized according to the general method of the quantum theory. Since the neutron and the proton both obey Fermi's statistics, the quanta accompanying the U-field should obey Bose's statistics and the quantization can be carried out on the line similar to that of the electromagnetic field.

The law of conservation of the electric charge demands that the quantum should have the charge either $+e$ or $-e$. The field quantity U corresponds to the operator which increases the number of negatively charged quanta and decreases the number of positively charged quanta by one respectively. $\tilde{U}$, which is the complex conjugate of U, corresponds to the inverse operator.

Next, denoting

$$p_x = -ih\frac{\partial}{\partial x}, \quad \text{etc.,} \quad W = ih\frac{\partial}{\partial t},$$

$$m_U c = \lambda h,$$

the wave equation for U in free space can be written in the form

$$\left\{p_x^2 + p_y^2 + p_z^2 - \frac{W^2}{c^2} + m_U c^2\right\} U = 0, \tag{12}$$

so that the quantum accompanying the field has the proper mass $m_U = \dfrac{\lambda h}{c}$.

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(6) These calculations were made previously, according to the theory of Heisenberg, by Mr. Tomonaga, to whom the writer owes much. A little modification is necessary in our case. Detailed accounts will be made in the next paper.

Assuming $\lambda=5\times10^{12}\mathrm{cm}^{-1}$., we obtain for m_U a value 2×10^2 times as large as the electron mass. As such a quantum with large mass and positive or negative charge has never been found by the experiment, the above theory seems to be on a wrong line. We can show, however, that, in the ordinary nuclear transformation, such a qnantum can not be emitted into outer space.

Let us consider, for example, the transition from a neutron state of energy W_N to a proton state of energy W_P, both of which include the proper energies. These states can be expressed by the wave functions

$$\Psi_N(x, y, z, t, 1)=u(x, y, z)e^{-iW_N t/h}, \quad \Psi_N(x, y, z, t, -1)=0$$

and

$$\Psi_P(x, y, z, t, 1)=0, \quad \Psi_P(x, y, z, t, -1)=v(x, y, z)e^{-iW_P t/h},$$

so that, on the right hand side of the equation (4), the term

$$-4\pi g\tilde{v}ue^{-it(W_N-W_P)/h}$$

appears.

Putting $U=U'(x, y, z)e^{i\omega t}$, we have from (4)

$$\left\{\Delta-\left(\lambda^2-\frac{\omega^2}{c^2}\right)\right\}U'=-4\pi g\tilde{v}u, \tag{13}$$

where $\omega=\dfrac{W_N-W_P}{h}$. Integrating this, we obtain a solution

$$U'(r)=g\iiint\frac{e^{-\mu|r-r'|}}{|r-r'|}\tilde{v}(r')u(r')dv', \tag{14}$$

where $\mu=\sqrt{\lambda^2-\dfrac{\omega^2}{c^2}}$.

If $\lambda>\dfrac{|\omega|}{c}$ or $m_Uc^2>|W_N-W_P|$, μ is real and the function $J(r)$ of Heisenberg has the form $-g^2\dfrac{e^{-\mu r}}{r}$, in which μ, however, depends on $|W_N-W_P|$, becoming smaller and smaller as the latter approaches m_Uc^2. This means that the range of interaction between a neutron and a proton increases as $|W_N-W_P|$ increases.

Now the scattering (elastic or inelastic) of a neutron by a nucleus can be considered as the result of the following double process: the neutron falls into a proton level in the nucleus and a proton in the latter jumps to a neutron state of positive kinetic energy, the total energy being conserved throughout the process. The above argument, then, shows that the probability of scattering may in some case increase

with the velocity of the neutron.

According to the experiment of Bonner[7], the collision cross section of the neutron increases, in fact, with the velocity in the case of lead whereas it decreases in the case of carbon and hydrogen, the rate of decrease being slower in the former than in the latter. The origih of this effect is not clear, but the above considerations do not, at least, contradict it. For, if the binding energy of the proton in the nucleus becomes comparable with $m_U c^2$, the range of interaction of the neutron with the former will increase considerably with the velocity of the neutron, so that the cross section will decrease slower in such case than in the case of hydrogen, i. e., free proton. Now the binding energy of the proton in C^{12}, which is estimated from the difference of masses of C^{12} and B^{11}, is

$$12{,}0036-11{,}0110=0{,}9926.$$

This corresponds to a binding energy 0,0152 in mass unit, being thirty times the electron mass. Thus in the case of carbon we can expect the effect observed by Bonner. The arguments are only tentative, other explanations being, of course, not excluded.

Next if $\lambda<\frac{|w|}{c}$ or $m_U c^2<|W_N-W_P|$, μ becomes pure imaginary and U expresses a spherial undamped wave, implying that a quantum with energy greater than $m_U c^2$ can be emitted in outer space by the transition of the heavy particle from neutron state to proton state, provided that $|W_N-W_P|>m_U c^2$.

The velocity of U-wave is greater but the group velocity is smaller than the light velocity c, as in the case of the electron wave.

The reason why such massive quanta, if they ever exist, are not yet discovered may be ascribed to the fact that the mass m_U is so large that condition $|W_N-W_P|>m_U c^2$ is not fulfilled in ordinary nuclear transformation.

§4. Theory of β-disintegration

Hitherto we have considered only the interaction of U-quanta with heavy particles. Now, according to our theory, the quantum emitted when a heavy particle jumps from a neutron state to a proton state, can be absorbed by a light particle which will then in consequence of energy absorption rise from a neutrino state of negative energy to an

(7) T. W. Bonner, Phys. Rev. 45, 606 (1934).

electron state of positive energy. Thus an anti-neutrino and an electron are emitted simultaneously from the nucleus. Such intervention of a massive quantum does not alter essentially the probability of β-disintegration, which has been calculated on the hypothesis of direct coupling of a heavy particle and a light particle, just as, in the theory of internal conversion of γ-ray, the intervation of the proton does not affect the final result.[8] Our theory, therefore, does not differ essentially from Fermi's thory.

Fermi considered that an electron and a neutrino are emitted simultaneously from the radioactive nucleus, but this is formally equivalent to the assumption that a light particle jumps from a neutrino state of negative energy to an electron state of positive energy.

For, if the eigenfunctions of the electron and the neutrino be ψ_k, φ_k respectively, where $k=1, 2, 3, 4$, a term of the form

$$-4\pi g'\sum_{k=1}^{4}\tilde{\psi}_k\varphi_k \tag{15}$$

should be added to the right hand side of the equation (5) for $\widetilde{U}$, where g' is a new constant with the same dimension as g.

Now the eigenfunctions of the neutrino state with energy and momentum just opposite to those of the state φ_k is given by $\varphi_k'=-\delta_{kl}\tilde{\varphi}_l$ and conversely $\varphi_k=\delta_{kl}\tilde{\varphi}_l'$, where

$$\delta=\begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix},$$

so that (15) becomes

$$-4\pi g'\sum_{k,l=1}^{4}\tilde{\psi}_k\delta_{kl}\tilde{\varphi}_l'. \tag{16}$$

From equations (13) and (15), we obtain for the matrix element of the interaction energy of the heavy particle and the light particle an expression

$$gg'\int\cdots\int\tilde{v}(\boldsymbol{r}_1)u(\boldsymbol{r}_1)\sum_{k=1}^{1}\tilde{\psi}_k(\boldsymbol{r}_2)\varphi_k(\boldsymbol{r}_2)\frac{e^{-\lambda r_{12}}}{r_{12}}dv_1dv_2, \tag{17}$$

corresponding to the following double process: a heavy particle falls

(8) H A Taylor and N F Mott, Proc Roy Soc A, 138, 665 (1932)

from the neutron state with the eigenfunction $u(r)$ into the proton state with the eigenfunction $v(r)$ and simultaneously a light particle jumps from the neutrino state $\varphi_k(r)$ of negative energy to the electron state $\psi_k(r)$ of positive energy. In (17) λ is taken instead of μ, since the difference of energies of the neutron state and the proton state, which is equal to the sum of the upper limit of the energy spectrum of β-rays and the proper energies of the electron and the neutrino, is always small compared with $m_U c^2$.

As λ is much larger than the wave numbers of the electron state and the neutrino state, the function $\frac{e^{-\lambda r_{12}}}{r_{12}}$ can be regarded approximately as a δ-function multiplied by $\frac{4\pi}{\lambda^2}$ for the integrations with respect to x_2, y_2, z_2. The factor $\frac{4\pi}{\lambda^2}$ comes from

$$\iiint \frac{e^{-\lambda r_{12}}}{r_{12}} dv_2 = \frac{4\pi}{\lambda^2}.$$

Hence (17) becomes

$$\frac{4\pi g g'}{\lambda^2} \iiint \tilde{v}(r) u(r) \sum_k \tilde{\psi}_k(r) \varphi_k(r) dv \qquad (18)$$

or by (16)

$$\frac{4\pi g g'}{\lambda^2} \iiint \tilde{v}(r) u(r) \sum_{k,l} \tilde{\psi}(r) \delta_{kl}' \tilde{\varphi}_l'(r) dv, \qquad (19)$$

which is the same as the expression (21) of Fermi, corresponding to the emission of a neutrino and an electron of positive energy states $\varphi_k'(r)$ and $\psi_k(r)$, except that the factor $\frac{4\pi g g'}{\lambda^2}$ is substituted for Fermi's g.

Thus the result is the same as that of Fermi's theory, in this approximation, if we take

$$\frac{4\pi g g'}{\lambda^2} = 4\times 10^{-50} \mathrm{cm}^3. \mathrm{erg},$$

from which the constant g' can be determined. Taking, for example, $\lambda = 5\times 10^{12}$ and $g = 2\times 10^{-9}$, we obtain $g' \simeq 4\times 10^{-17}$, which is about 10^{-8} times as small as g.

This means that the interaction between the neutrino and the electron is much smaller than that between the neutron and the proton so that the neutrino will be far more penetrating than the neutron and consequently more difficult to observe. The difference of g and g' may be due to the difference of masses of heavy and light particles.

§ 5. Summary

The interaction of elementary particles are described by considering a hypothetical quantum which has the elementary charge and the proper mass and which obeys Bose's statistics. The interaction of such a quantum with the heavy particle should be far greater than that with the light particle in order to account for the large interaction of the neutron and the proton as well as the small probability of β-disintegration.

Such quanta, if they ever exist and approach the matter close enough to be absorbed, will deliver their charge and energy to the latter. If, then, the quanta with negative charge come out in excess, the matter will be charged to a negative potential.

These arguments, of course, of merely speculative character, agree with the view that the high speed positive particles in the cosmic rays are generated by the electrostatic field of the earth, which is charged to a negative potential.[9]

The massive quanta may also have some bearing on the shower produced by cosmic rays.

In conclusion the writer wishes to express his cordial thanks to Dr. Y. Nishina and Prof. S Kikuchi for the encouragement throughout the course of the work.

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CHAPTER ONE

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CHAPTER TWO

Hyperfine Structures, Nuclear Moments, and Spin

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CHAPTER THREE

Scattering and Collision Processes

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CHAPTER FOUR

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CHAPTER FIVE

Radioactivity

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CHAPTER SIX

Beta Radiation

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CHAPTER SEVEN

Gamma Radiation

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CHAPTER EIGHT

Neutrons

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CHAPTER NINE

Theory of Nuclear Structure

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CHAPTER TEN

Theories of Disintegration Processes

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CHAPTER ELEVEN

Nuclear Fission

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CHAPTER TWELVE

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Amer. J. Phys.	American Journal of Physics. New York.
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Ann. Phys., Leipzig	Annalen der Physik. Leipzig.
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Astrophys. J.	Astrophysical Journal. Chicago.
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Ber. Deutsch. Chem. Ges.	Berichten der deutschen chemischen Gesellschaft. Berlin.
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Gött. Nachr.	Königliche Gesellschaft der Wissenschaften zu Göttingen. Nachrichten. Göttingen.

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K. Fys. Sallsk. Lund, Förh.	Kungliga Fysiografiska Sallskapets i Lund Forhandlingar. Lund, Sweden.
K. Ned. Akad. Verh.	Koninklijke Akademie van Wetenschappen, Verhanelingen. Amsterdam.
Kgl Danske Vid. Sels	Kongelige Danske Videnskabernes Selskab. Copenhagen.
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